FIRESAFE II
Detection and Decision

Final Report

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1 ABSTRACT

Early detection of fire and quick activation of the fire extinguishing system are often considered as the main keys to successful fire management, allowing to prevent loss of life and damage to the ship and cargo.

This report presents a Formal Safety Assessment on detection and on decision of extinguishing system activation following a ro-ro space fire incident on any ro-ro passenger ship.

The safety level was estimated for three generic ships representing the world fleet of RoPax ships (*Cargo*, *Standard*, and *Ferry RoPax*) and a cost-effectiveness assessment was performed on six Risk Control Options (RCO), taking into account potential differences between newbuildings and existing ships.

From a detection perspective, only the RCO *Combined smoke and heat detection* was found cost-effective for *Standard* and *Ferry* newbuildings (but not for existing ships).

From a decision perspective, the RCO *Improved markings/signage for way-finding and localisation* and *Alarm System Design & Integration* met the cost-effectiveness criteria on all three generic ships, except for the Existing *Cargo RoPax* ships for the latter RCO. The RCO *Preconditions for Early Activation of Drencher System* was found cost-effective for *Standard* and *Ferry RoPax* ships.

2 EXECUTIVE SUMMARY

Early detection of fire and quick activation of the fire extinguishing system are often considered as the main keys to successful fire management, allowing to prevent loss of life and damage to the ship and cargo. New means for early detection and for quick decision-making of extinguishing system activation are investigated in this report. These aspects were not investigated into detail in the previous FIRESAFE study, where they were judged and considered in the same node of the risk model: early decision for activation.

The main objective of FIRESAFE II was to improve the fire safety of ro-ro passenger ships by cost-efficient safety measures reducing the risk of ro-ro space fires, with an aim to discuss specific proposals for rule making. In Part 1 of the study, reported here, the objective was to identify a range of risk control options (RCOs) and to assess the ones most likely to be cost efficient in relation to fire detection as well as to the decision to activate the fire-extinguishing system.

The study considered open ro-ro spaces, closed ro-ro spaces as well as weather decks, for both newbuildings and existing ships.

The Formal Safety Assessment (FSA) methodology was followed, as described in the Guidelines MSC-MEPC.2/Circ.12/Rev.2. The FSA is a structured and systematic methodology aimed at enhancing maritime safety and consists of the following five steps:

- Step 1: Hazard identification;
- Step 2: Risk analysis;
- Step 3: Risk control options;
- Step 4: Cost-effectiveness assessment; and
- Step 5: Recommendations for Decision-Making.

In order to perform the investigation of fire detection and decision of extinguishing system activation in line with the FSA methodology, a review of regulations and current practices concerning fire detection systems and the decision-making processes was also first conducted.

To consider the diverse world fleet of RoPax ships in the study, three generic categories of ships were defined based on a lane metre to passenger capacity ratio:

- *Ferry RoPax*, represent RoPax ships or ferries with focus on carriage of passengers but which can also carry cargo similar to a *Standard RoPax*. These ships typically only have closed ro-ro spaces or mainly closed ro-ro spaces and a small weather deck;
- *Standard RoPax*, represent the RoPax ships with focus on both carriage of cargo and of passengers. These vessels typically have each of the three types of ro-ro spaces: closed ro-ro spaces, open ro-ro spaces and weather decks. The size of the weather deck/s is generally medium to large within this category; and
- *Cargo RoPax*, represent RoPax ships with focus on carriage of cargo and basically have a passenger capacity just enough to carry the number of drivers necessary to load the ro-ro spaces with accompanied trailers. These vessels typically have closed ro-ro spaces and large weather deck/s.

Both hazards that have materialized in the past and those that have not been experienced (yet) were identified through analytical and creative techniques to produce a list of hazards relevant to detection failure and decision failure.

For the detection part, some notable results from the hazard identification were:

- The detection system is often deactivated during loading and discharging as well as during maintenance operations. This often implies deactivation of many or all ro-ro spaces;
- It is difficult to detect the fire at its early stage of development if the fire develops inside cargo or a vehicle;
- The environment in ro-ro spaces is quite harsh, and it is not uncommon that dirt, salt, exhaust fumes etc. clog the detectors;

- The detection system alarm panel can be illogical (confusion regarding the detection frame number, detection section, drencher section, Closed-Circuit Television (CCTV) numbering, etc.) which could imply delayed first response and delayed extinguishing system activation;
- No detection system is required for weather deck;
- The frequency of fire patrols is undefined and generally quite low;
- The accessibility within ro-ro spaces is very limited, which makes manual detection and fire localisation difficult; and
- Many false alarms reduce the motivation of crew to quickly attend to alarms.

For decision of extinguishing system activation, some notable results from the hazard identification were:

- Alarm system management (e.g. information presentation, coherence, noise levels);
- Runner deployment (e.g. speed of deployment);
- Way finding, localisation and relevant support (e.g. familiarity, markings, signage);
- Assembly of key decision-makers (e.g. availability);
- Resource management on the bridge (e.g. competing goals/processes, fire management in relation to regular operations);
- Drencher activation mandate (including hierarchy, blame culture);
- Assessment of fire characteristics, environment and fire spread;
- Ventilation management (smoke removal vs. supply of more oxygen to the fire);
- Maintenance of knowledge and competence (e.g. realism in training); and
- Communication issues (between bridge, fire scene, drencher station, engine room).

The definition of Early/Late Decision has remained the same as in FIRESAFE. “Early” and “Late” decision should be understood in relation to the fire growth rate. “Early” means that the Decision to activate the system has been taken early enough to have a chance to extinguish the fire. “Late” means that the fire is already quite developed, and that it is too late to have a chance to extinguish it. However, the fire can still be suppressed upon system activation. In FIRESAFE, the Early/Late Decision concept included fire detection, but in FIRESAFE II it was considered separately.

The new concept introduced for Early/Late detection is related to whether it is possible to successfully perform first response and extinguish the fire in its initial stage. The criterion for “Early” detection is that the *Available Time for Safe First Response* (the time available until conditions become untenable around the fire, disallowing first response) is longer than the *Required Time for Safe First Response* (the time to detect the fire and to set up all actions for first response). Otherwise, the detection is considered to be too late to be able to extinguish the fire at its initial stage (for example with a hand-held fire extinguisher), based on that this cannot be done safely.

A review and update of the main fire risk model was made based on the above updated definitions. This led to the introduction of dedicated branches in the event tree for *Detection*, *First response*, and *Decision*.

Dedicated fault trees were developed focusing on the main hazards identified during the Hazard Identification (HazId). The trees were quantified to gain an understanding of the impacts on risks and to investigate in further detail the important causes and initiating events of the accident scenarios identified. This allowed quantification of the contributing detection failures as well as to calculate the overall detection failure rate. In order to consider the different types of ro-ro spaces, different trees were developed and quantified by investigation of available failure data, fire simulations and expert judgement, in case none of the previous options were available. A similar exercise was performed for Decision fault tree.

The main fire risk model and the associated sub-models were developed in such a way that it is possible to assess, in quantitative values, the consequences of additional preventing and mitigating measures addressing the risks of detection and decision failures.

For the detection part, a range of Risk Control Measures (RCM) was identified based on the hazards identified in previous steps and on proposals of RCMs identified in former projects. All the measures presumed an existing fire and were classified as mitigating, rather than preventive. The RCMs were ranked by experts with regard to risk reduction potential and estimated costs. Some of these RCMs were considered as “low hanging fruit”, meaning RCMs with low estimated cost that do not necessitate further evaluation and which can be recommended as voluntary measures to reduce the risk.

Based on the ranking and on the high-risk areas needing control in the fault tree, the RCMs with the highest potential were judged to be:

- Combined smoke and heat detection;
- Fibre optic linear heat detection (for open and closed ro-ro spaces);
- Ban / closure of side (Portside & Starboard) openings (open ro-ro spaces);
- Increased frequency of fire patrols;
- CCTV covering all decks;
- Thermal imaging cameras on weather decks;
- Flame detection on weather decks;
- Better addressability;
- Detector drone or camera on rail; and
- Additional detection means in Alternatively Fuelled Vehicles areas.

Three of the above RCMs were selected as Risk Control Options (RCOs) for further quantitative cost-effectiveness analysis, based on their perceived cost-effectiveness, Technology Readiness Level (TRL), and availability:

- Combined smoke and heat detection: A review of the regulations and common practices showed that smoke detection is often the only means for fire detection used in ro-ro spaces. However, the review of previous accidents and the HazId showed that heat detection could provide a way to detect some types of fire earlier and an alternative way of detecting a fire when smoke detectors are deactivated during loading and discharging of the decks. Combined point heat and smoke detectors were investigated to replace conventional smoke detectors;
- Ban / closure of side (Portside & Starboard) openings (open ro-ro spaces): Heat and smoke movements are affected by the airflow and hence by the gusts coming from the side openings. This results in increased detection times, and in case the fire is close to an opening it can remain unnoticed for a long time. Closing the side openings of open ro-ro spaces was investigated for existing ships and the ban of open ro-ro spaces was considered for newbuildings; and
- Increased frequency of fire patrols: Many fires are caused due to electrical problems, which often means overheated components or cables and a long incipient phase with smouldering fire. These may produce too little smoke to be detected by the smoke detectors. However, if passing through the space, fire patrols are more likely to give early detection of incipient fires compared to automatic fire detection systems. An increased frequency of fire patrols would imply an increased probability of a patrol passing the fire during the incipient phase and thus a higher probability of early detection. A half-hour interval between fire patrols was investigated in this study.

For the decision part, the hazards identified in previous steps and feedback collected from crew members revealed a number of conditions that may have profound impacts on early decision of extinguishing system activation. A wide range of Risk Control Measures was listed and this list was narrowed down to focus on the Risk Control Measures that are directly related to decision-making, as defined in FIRESAFE II. All the measures that have a too low TRL were discarded before the preliminary assessment and the measures left were structured into 6 realistic and self-sufficient RCMs:

- Alarm System Design & Integration;
- Improved markings/signage for way-finding and localization;
- Technical aids for fire identification and monitoring;
- CCTV system for fire identification and monitoring;
- Spacing of cargo for accessibility; and
- Preconditions for Early Activation of Drencher System.

These RCMs were ranked by experts with regard to risk reduction potential and estimated costs. Based, on this ranking, three risk control options were selected for further quantitative cost-effectiveness analysis:

- Alarm System Design & Integration: Reviews and interviews made within FIRESAFE II have shown that alarm systems and their interfaces are often lacking both in terms of the information they offer and how this information is presented to the user. A lack of relevant and immediately accessible information can cause severe delays in decision-making, allowing the fire to expand, thereby creating an even more difficult operative situation. This RCO considers an alarm system that fully supports fire incident decision-making, as well as other resources on the bridge relevant for fire-related decision-making designed to provide immediate, precise and accessible information to support the localisation of a fire;

- Improved markings/signage for way-finding and localization: A common response in the event of a fire alarm is to send a runner to the point of detection with the task of confirming or disconfirming the existence of a fire. Crew familiarization plays a part in this task, as well as the tightly packed ro-ro space environment. Furthermore, given that the situation might be stressful, runners may sometimes have difficulties in determining their exact location, which is important information to the bridge e.g. for drencher activation. This RCO investigates the impact of improved signage and markings in the ro-ro space supporting wayfinding and orientation in case of fire. They shall be designed for easy identification and interpretation by a variety of users representing normal individual variations; and
- Preconditions for Early Activation of Drencher System: Studies within FIRESAFE II have shown that there will often be a reluctance towards drencher activation among the crew, either because of a lack of decision mandate, unfamiliarity with the drencher system and drencher room environment, or fear of any negative consequences that could be the result of faulty activation. This RCO consists in the inclusion of the early activation of the drencher system in fire management procedures while also ensuring that a large portion of the crew has the knowledge and mandate for drencher activation, without fear of negative consequences for the individual crewmember.

The estimated risk reduction effect of the above RCOs were quantified by investigation of available failure data, fire simulations and expert judgement, in case none of the previous options were available. By applying each of the risk control options to the risk model (event tree), the risk reduction of all selected RCOs was calculated.

Costs for the implementation of these RCOs were estimated. Technical items available on the market were as far as possible quantified by system supplier offers. In addition, cost estimations were based on existing costs for material from ship operator’s internal projects, specifications, reconstructions, etc. The main component systems of each RCO were identified and respective costs were estimated. For any operational RCOs, manning and training costs were used based on ship operator’s experience. Other cost items affecting for example operations were included in the quantification when necessary.

The cost-effectiveness criteria were updated. A RCO was considered cost-effective if the Gross Cost of Averting a Fatality (GCAF) is below €7 M. A RCO was also considered cost effective if the Net Cost of Averting a Fatality (NCAF), accounting for the economic benefits of the RCO, is below €7 M.

The findings of the cost-effectiveness assessment is summarised in the below table.

		Newbuildings			**Existing Ships**		
	RCO	***Cargo RoPax***	***Standard RoPax***	***Ferry RoPax***	***Cargo RoPax***	***Standard RoPax***	***Ferry RoPax***
Detection	Combined heat & smoke detection	Not cost-effective	Cost-effective	Cost-effective	Not cost-effective	Not cost-effective	Not cost-effective
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	Not applicable	Not cost-effective	Not applicable	Not applicable	Not cost-effective	Not applicable
	Increased frequency of fire patrols	Not cost-effective	Not cost-effective	Not cost-effective	Not cost-effective	Not cost-effective	Not cost-effective
Decision	Alarm System Design & Integration	Cost-effective	Cost-effective	Cost-effective	Not cost-effective	Cost-effective	Cost-effective
	Improved markings for wayfinding and localisation	Cost-effective	Cost-effective	Cost-effective	Cost-effective	Cost-effective	Cost-effective
	Preconditions for Early Activation of Drencher System	Not cost-effective	Cost-effective	Cost-effective	Not cost-effective	Cost-effective	Cost-effective

The FSA demonstrated that the following RCOs achieved the highest risk reduction in a cost-effective manner (ranked from highest to lowest risk reduction):

- For Newbuildings:
  - Regardless of the ship category:
    - Alarm System Design and Integration; and
    - Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - Preconditions for Early Activation of Drencher System; and
    - Combined heat and smoke detection.
- For Existing ships:
  - Regardless of the ship category:
    - Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - Preconditions for Early Activation of Drencher System; and
    - Alarm System Design and Integration.

It should also be noted that the relative risk reductions of the RCOs only take into account the effects of the RCOs on the respective Detection and Decision nodes in the main fire risk model. However, any effects that the RCOs could have directly on the other main branches of the main fire risk model event tree were disregarded which may render cost-effective some RCO that were not in this part (no negative side effects expected). These considerations were taken into account in the Combined Assessment part of the FIRESAFE II study (EMSA, 2018).

Finally, recommendations on how the cost-effective RCOs could be implemented were discussed.

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6 INTRODUCTION

6.1 Scope and Objectives

The main objective of FIRESAFE II was to improve the fire safety of ro-ro passenger ships by cost-efficient safety measures reducing the risk of ro-ro space fires, with an aim to discuss specific proposals for rule making. In Part 1 of the study, reported here, the objective was to identify a range of risk control options (RCOs) and assess the ones most likely to be cost efficient in relation to fire detection as well as to the decision to activate the fire-extinguishing system, considering open ro-ro spaces, closed ro-ro spaces as well as weather decks, for both newbuildings and existing ships.

6.2 Background

In 2016, EMSA initiated the FIRESAFE study in order to investigate cost-efficient measures for reducing the risk from fires on ro-ro passenger ships, with a focus on Electrical Fire as ignition source as well as Fire Extinguishing Failure. These areas were considered the greatest risk contributors by the EMSA Group of Experts on fires on ro-ro decks.

The study produced a main fire risk model covering the various stages of a fire incident on a ro-ro space of a ro-ro passenger ship, namely: ignition, detection/decision, extinguishment, containment and evacuation.

In 2017, EMSA initiated the FIRESAFE II study to investigate risk control options for mitigating the risk from fires in ro-ro spaces in relation to Detection and Decision (Part 1) as well as Containment and Evacuation (Part 2), which are items which were not addressed specifically in FIRESAFE.

Two additional parts, one focusing on alternative fixed fire-extinguishing systems for ro-ro decks (Part 3), and one part focusing on detection systems in open ro-ro spaces and weather decks (Part 4) were also included.

Early detection of fire and quick activation of the fire extinguishing system are often considered as the main keys to successful fire management, allowing to prevent loss of life and damage to the ship and cargo. New means for early detection and for quick decision-making of extinguishing system activation are investigated in this report. These aspects were not investigated into detail in the previous FIRESAFE study, where they were judged and considered in the same node of the risk model: early decision for activation.

In this new study, this specific node was analytically investigated and separated into two main components, namely detection and decision.

6.3 Methodology

In order to achieve the objectives described in section 6.1, the Formal Safety Assessment methodology was followed.

A summary of the steps detailed in the “Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process” (IMO, 2018) is provided below:

- Problem Definition: The objective of this task is to clarify the objectives and clearly define the scope of the study. This was done through an analysis of the RoPax fleet, of relevant regulations, requirements and current practices related to detection and decision. In particular, the problem definition leads to the development of generic ships. The details of this task are described in Chapter 7;
- 1st step: Identification of Hazards: The purpose of this step is to identify relevant hazards to the safety matter under consideration. Both hazards that have materialized in the past and those that have not been experienced (yet) were identified through analytical and creative techniques. The details of this step are described in Chapter 8;
- 2nd step: Risk Analysis: The purpose of this step is to investigate in further detail the causes and initiating events of the accident scenarios identified in the 1st step. A main fire risk model and dedicated fault trees were developed and quantified for this purpose and are detailed in Chapter 9;

- 3rd step: Risk Control Options: The purpose of this step is to identify Risk Control Measures and propose potential Risk Control Options for reducing the risk. Relevant risk control options are selected and their technical specifications and risk reduction potential are further described. The details of this step are described in Chapters 10 and 11.
- 4th step: Cost-Effectiveness Assessment: In this step, the RCOs selected in Chapter 10 are analysed in a way to facilitate the understanding of the costs and benefits resulting from the potential adoption of such RCOs. This results in a ranking of the RCOs from a cost-efficiency perspective. The results of this step are provided in Chapter 12; and
- 5th step: Recommendations for Decision-Making. Based on the above tasks, and in particular the cost-effectiveness assessment, specific proposals for rule making are discussed. These discussions are presented in Chapter 13.

7 BACKGROUND INFORMATION

7.1 Analysis of the RoPax fleet

7.1.1 *Selection criteria*

The objective of FIRESAFE II was to investigate cost efficient measures for reducing the risk from fires on ro-ro passenger ships with a view to propose amendments to the relevant regulatory instruments. In this regard, only SOLAS compliant ships were of interest for the study.

Therefore, the world fleet of ro-ro passenger ships were restricted to vessels:

- classed as Passenger/Ro-Ro Ship;
- engaged on international voyages or EU domestic class A;
- gross tonnage equal or greater than 1,000;
- with a build date on or after 01/01/1970;
- Froude number less than 0.5[1]; and
- classed or having been classed by one the IACS members.

All these criteria, with the exception of the Build Date, are similar to the ones used in FIRESAFE. Explanations and justification for these criteria were extensively reported in the FIRESAFE study (EMSA, 2016).

7.1.1.1 Build Date

In FIRESAFE, choice was made to consider only ships which keel was laid on or after 25 May 1980 (date of entry into force of the SOLAS 1974).

Although the SOLAS 1960 is very vague about garage spaces, the concept of horizontal zone was first defined properly, together with fire protection measures dedicated to passenger ship garage spaces, by Resolution A.122, also known as part H, which was adopted in 1967 by the IMO assembly.

This Resolution was never formally ratified and therefore remained of voluntary application - but made mandatory by a number of Administrations - until these amendments were incorporated in Chapter II-2 of the 1974 Convention. In that sense, most ships built according to Part H might be considered as having the same safety level as those built according to SOLAS 1974 as acknowledged by the Resolution MSC.24(60) (IMO, 10 April 1992).

For this reason, ships built[2] on or after 01/01/1970 were considered in the dataset.

7.1.2 *Analysis of the FIRESAFE II Fleet*

The FIRESAFE II fleet is composed of 842 ships active during the period 1994-2016 and 811 during the period 2002-2016. For reference, in FIRESAFE, 490 ships were active during the period 1994-2015 and 488 during the period 2002-2015.

In order to gain more insight into the fleet being looked at, the main characteristics investigated in FIRESAFE were updated with the new set of data and are reported in the following sections.

7.1.2.1 Shipyears

The number of shipyears was calculated for the time between the effective date of entry into IACS class (as reported in IHS) or “start of the period of study”, and either one of the following:

- end of the period of study (31/12/2016);

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[1] To exclude High Speed Crafts.

[2] Build date is described as "Date of Build which in nominally referred to as the actual or expected date of delivery for vessels after construction.”

- the scrap date or date of loss; or
- the date of withdrawal of IACS class.

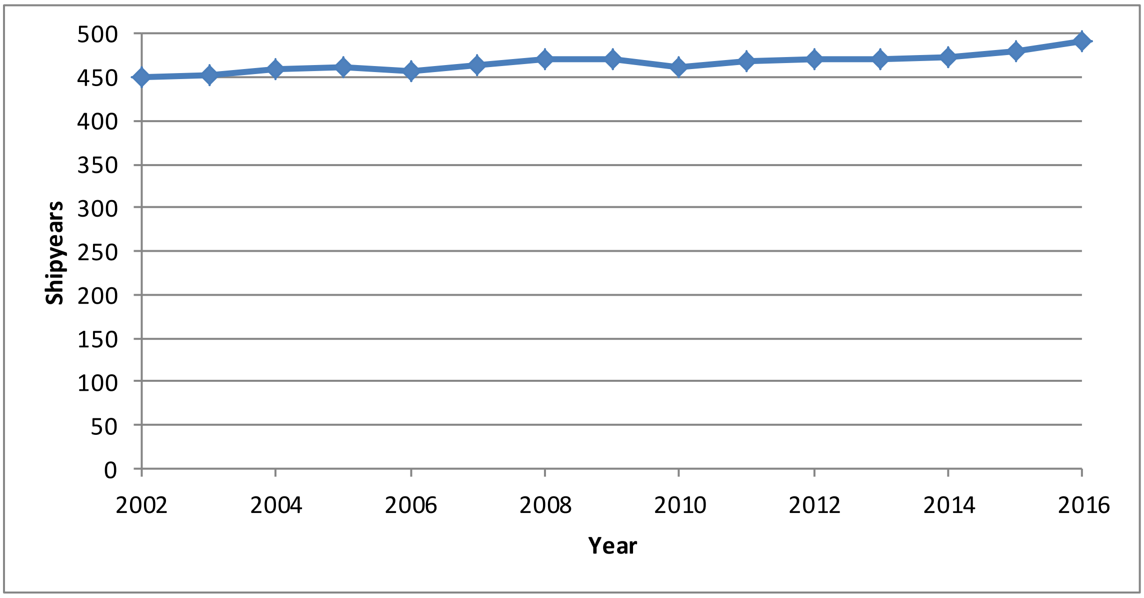

Figure 1: Number of shipyears per year for the FIRESAFE II fleet between 2002 and 2016

Figure 1 shows the number of shipyears per year for the FIRESAFE II fleet between 2002 and 2016. The number of shipyears is slightly increasing from 450 shipyears in 2002 to around 490 shipyears in 2016.

This leads to a total of 7001 shipyears over the period 2002 – 2016.

7.1.2.2 Age

Figure 2 shows the number of shipyears with respect to the age of ships over the period 2002-2016. This figure shows a very slight decreasing trend up to around 32 years old, which is the average loss age, then the number of shipyears decreases gradually until 46 years old.

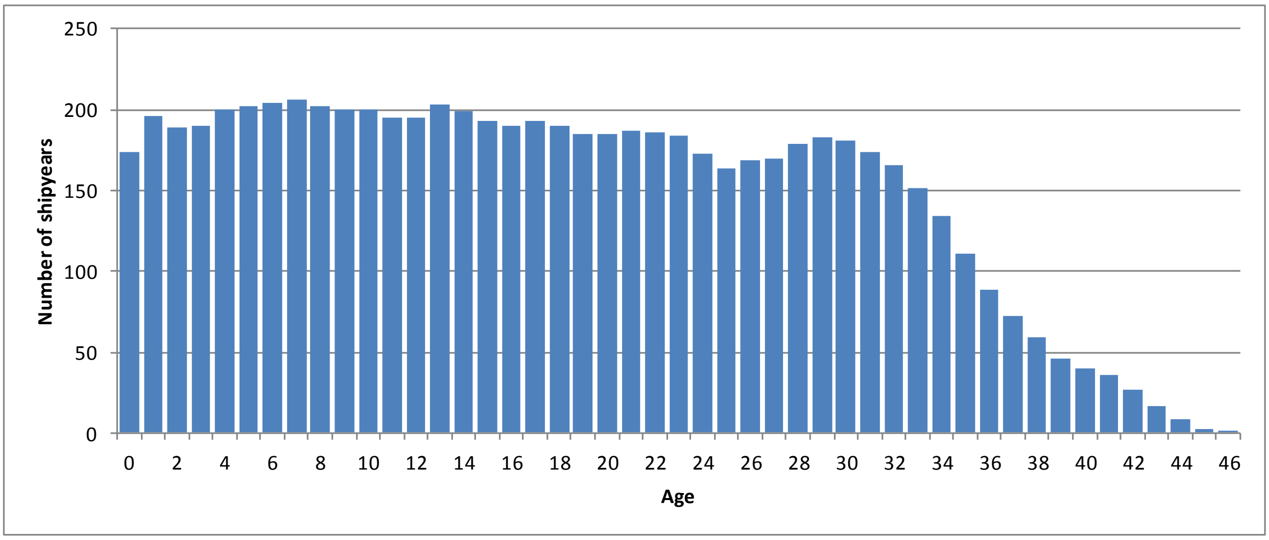

Figure 2: Number of shipyears for ships observing the given age during the period 2002-2016

Figure 3 shows the average age of the fleet for the period 2002-2016. The age of a ship is calculated from the 31st of December of each year.

The average age is slightly increasing from year to year to reach 20 years old in 2016.

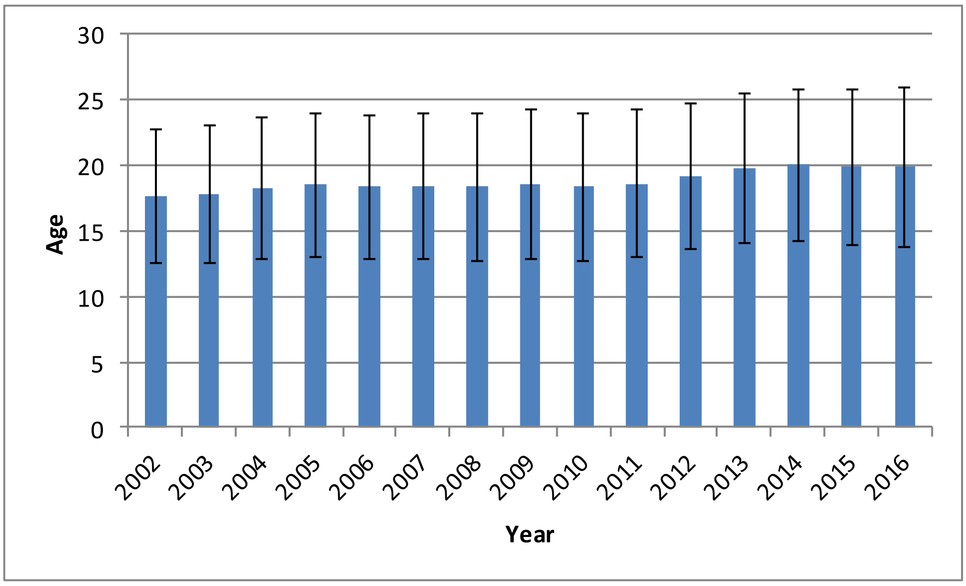

Figure 3: Average age of the fleet between 2002 and 2016 (+/- one standard deviation)

In a similar way to FIRESAFE, although the observed increase in the average age of the fleet over the investigated period is gentler, it might be argued that the fleet selected is not homogenous and that it affects the incident rate. By normalizing the number of accidents for each age with the exposure time (which was plotted shown in Figure 2), it was possible to determine the accident frequency as a function of the ship age. This was investigated in the paragraph 8.1.2.4.

Life expectancy (at delivery) over the period 2002-2016 for the ships of the FIRESAFE II fleet was estimated to 39.2 years old.

7.1.2.3 Fleet evolution: gross tonnage

Figure 4 shows the evolution of the average gross tonnage of the fleet under consideration over the period 2002-2016. A slight increase can be observed between 2002 and 2012, followed by a slight decrease until 2016 to reach 21120 GT. This pattern was already observed in FIRESAFE.

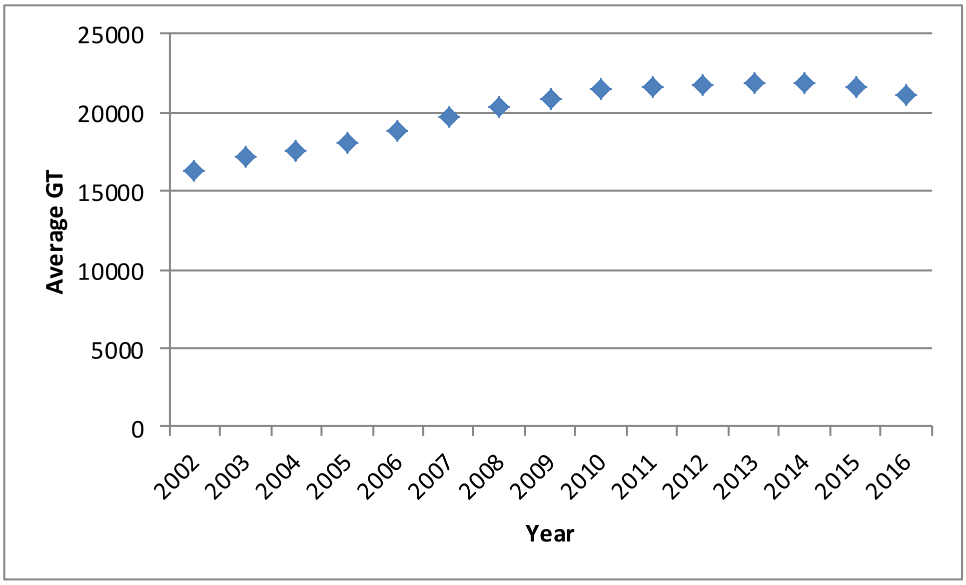

Figure 4: Evolution of the average gross tonnage of the FIRESAFE II fleet over the period 2002-2016

7.2 Overview of relevant regulations and requirements (detection and decision)

7.2.1 *General*

7.2.1.1 Introduction

7.2.1.1.1 Scope

This section aims at giving an overview of fire detection requirements applicable in ro-ro spaces of passenger ships.

Based on SOLAS and as detailed in 7.2.2, a fixed fire detection system is required in the ro-ro spaces of passenger ships. On ships constructed after 07/2010 this system is to be addressable complying with the requirements of FSS Code Ch.9.

7.2.1.1.2 Applicable regulations

It is to be noted that the present review is based on the currently applicable regulations. Therefore, some of the requirements detailed below may not be applicable on old ships. As an indication, FSS Code Chapter 9, dedicated to fixed fire detection systems was fully reviewed through MSC.311(88) and applies to ships the keel of which was laid after 01/07/2012. However, only few significant changes in the regulations were identified over the last 40 years. A brief summary of the main regulation changes related to fire safety in ro-ro spaces of passenger ships is provided in Table 1.

Table 1: Summary of regulation changes

Adoption date	Application date	Regulation change	Summary
1974	1980[3]	SOLAS 74	Introduces the principle of horizontal fire zone for ro-ro spaces / special category spaces with: • Structural fire protection • Fixed fire extinguishing system ("drencher" type) • Fixed fire detection system
2008	2008	MSC.1/Circ.1272	Allows water-mist fixed fire-extinguishing systems Allows automatic release
2006	2010	MSC.217(82)	Requires addressable fixed fire detection and fire alarm systems on passenger ships
2010	2012	MSC.311(88)	Revision of FSS Code Ch.9

As a general remark, there are very little specific requirements related to fire detection in Classification and Flag Rules. This topic is mainly covered by IMO Regulations and a few IACS texts. Therefore, the review was mainly based on the IMO and IACS documents listed in Table 2.

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[3] It is to be noted that the concept of horizontal fire zone and associated safety measures has actually been introduced in SOLAS 60 part H as per IMO resolution A.122(V) dated October 1967. However, the circular was never made mandatory and Part H was therefore only applied on a voluntary basis until SOLAS 74 came into force. Compliance with Part H is formally recognized to be equivalent with SOLAS 74.

Table 2: List of documents used for the review of regulations of fire detection requirements applicable in ro-ro spaces of ro-ro passenger ships

IMO Documents	Safety of Life at Sea (SOLAS) Convention, as amended in 2017
	Fire Safety Systems (FSS) Code, as amended in 2017
	MSC/Circ.1035 – Guidelines for the use and installation of detectors equivalent to smoke detectors
	MSC.1/Circ.1242 – Guidelines for approval of fixed fire detection and fire alarm systems for cabin balconies
	MSC.1/Circ.1369 – Interim explanatory notes for the assessment of passenger ship systems' capabilities after a fire or flooding casualty
	MSC.1/Circ.1430 – Revised guidelines for the design and approval of fixed water-based fire-fighting systems for ro-ro spaces and special category spaces, May 31, 2012
	MSC.1/Circ.1437 – Unified interpretation of SOLAS II-2/21.4
IACS Documents	UI SC35 rev.3 – July 2013 "Fixed Fire Detection and Fire Alarm System"
	UI SC73 rev.2 – Nov. 2005 "Fire protection of weather decks"
	UI SC117 rev.2 – Nov. 2005 "Fire detection system with remotely and individually identifiable detectors"
	UR E22 rev.2 – June 2016 "On Board Use and Application of Computer based systems"
Classification Rules	BV Rules for Steel Ship (NR467), as amended in January 2018
	BV NR598 "Implementation of Safe Return to Port and Orderly Evacuation" dd. January 2016
	DNVGL Rules for the Classification of Ships, January 2017
	LR Rules and Regulations for the Classification of Ships, July 2016
	NKK Rules for the Survey and construction of Steel Ships, June 2016
Flag Administration Rules	MMF (French Flag Administration) Division 221 "Passenger ships engaged in international voyages and cargo ships of more than 500 gross tonnage", 04/08/17 edition
	US Coast Guard Code of Federal Regulations (CFR) 46, 2017 online edition
	Swedish Transport Agency (Swedish Flag Administration) "Comments and interpretations by the Swedish Transport Agency regarding IMO Conventions", version 03 dd.15/05/2017
	MCA (UK Flag Administration) Guidance on SOLAS Ch.II-2

7.2.1.1.3 Regulation mapping

Specific attention was given to the “fire detection failure” branch of tier 2 – Fire growth schematic tree proposed by the EMSA group of experts on fires on ro-ro decks, resulting in the regulation mapping detailed in Figure 5. At the end of each branch, reference is made to the relevant paragraphs of 7.2.2 of this section, in which the content of the relevant regulation is summarized.

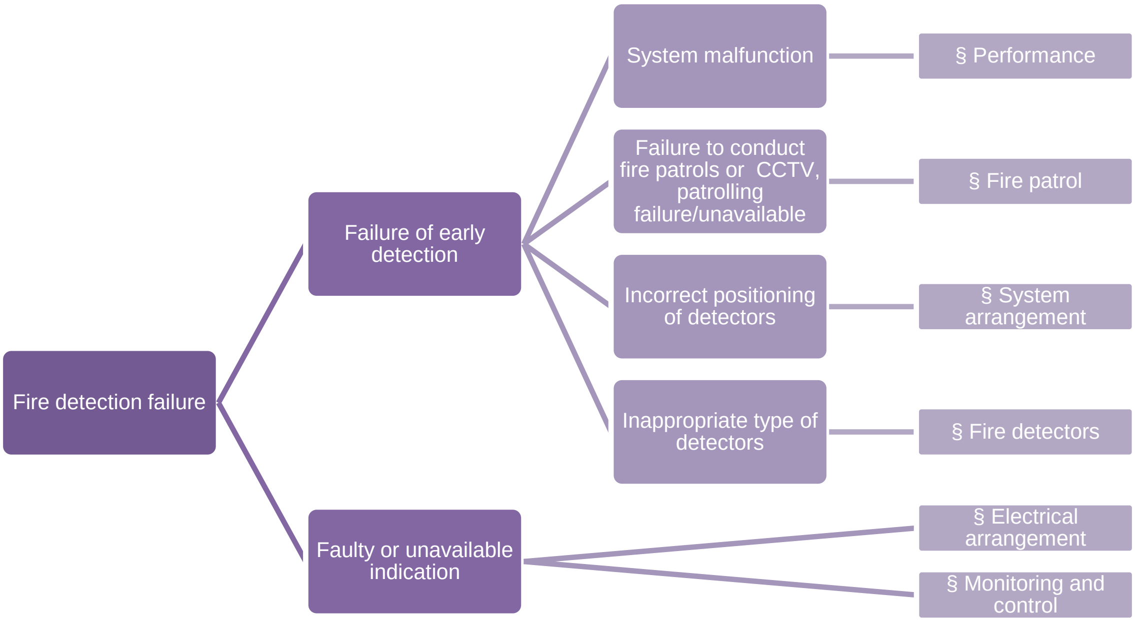

Figure 5: Regulation mapping for fire detection failure in the ro-ro spaces of passenger ships

7.2.1.2 Definitions

7.2.1.2.1 Ro-ro space, vehicle space and special category space

As per SOLAS II-2/3:

- “Vehicle spaces are cargo spaces intended for carriage of motor vehicles with fuel in their tanks for their own propulsion.”
- “Ro-ro spaces are spaces not normally subdivided in any way and normally extending to either a substantial length or the entire length of the ship in which motor vehicles with fuel in their tanks for their own propulsion and/or goods (packaged or in bulk, in or on rail or road cars, vehicles (including road or rail tankers), trailers, containers, pallets, demountable tanks or in or on similar stowage units or other receptacles) can be loaded and unloaded normally in a horizontal direction.”[4]
- “Special category spaces are those enclosed vehicle spaces above and below the bulkhead deck, into and from which vehicles can be driven and to which passengers have access. Special category spaces may be accommodated on more than one deck provided that the total overall clear height for vehicles does not exceed 10 m.”

  Special category spaces are ro-ro spaces to which passengers have access, possibly during the voyage. Special category spaces are the most frequent type of closed ro-ro spaces on ro-ro passenger ships.

  It is to be noted that open ro-ro spaces are not considered as special category spaces.

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[4] In other words, ro-ro spaces are vehicle spaces into which vehicles can be driven. It is to be noted however that, for the purpose of the application of SOLAS II-2/19, the following interpretation can be found in MSC.1/Circ.1120 and IACS UI SC 85: “Ro-ro spaces include special category spaces and vehicle spaces”

7.2.1.2.2 Closed, open and weather deck

As per SOLAS II-2/3:

- A “weather deck is a deck which is completely exposed to the weather from above and from at least two sides.”
- IACS UI SC 86 additionally details that: “For the purposes of Reg. II-2/19 a ro-ro space fully open above and with full openings in both ends may be treated as a weather deck.”
- For practical purposes, drencher fire-extinguishing system cannot be fitted on weather decks due to the absence of deckhead. This criterion is often used for a practical definition of weather decks.
- An open vehicle or ro-ro space is “either open at both ends or [has] an opening at one end and [is] provided with adequate natural ventilation effective over [its] entire length through permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10% of the total area of the space sides.”
- A closed vehicle or ro-ro space is any vehicle or ro-ro space which is neither open nor a weather deck.

  As a reference criterion, it can be considered that a vehicle space that needs mechanical ventilation is a closed vehicle space.

7.2.2 *Requirements*

7.2.2.1 Type of systems, spaces to be covered

7.2.2.1.1 General requirement

SOLAS II-2/20.4.1 requires a fixed fire detection and fire alarm system to be fitted in all ro-ro spaces.

It is widely accepted however that no fixed fire detection and fire alarm system is required on weather decks used for the carriage of vehicle with fuel in their tanks as per IACS interpretation UI SC73.

It is to be noted that fire detection is required on open ro-ro spaces (although some discussion on this point regularly arises at shipbuilding phase).

7.2.2.1.2 Special category spaces

In special category spaces, however, SOLAS II-2/20.4.3.1 allows that “If an efficient fire patrol system is maintained **by a continuous fire watch** at all times during the voyage, a fixed fire detection and fire alarm system is not required.”

It is to be noted that some Flag States require a fixed fire detection system, independently of the existence of continuous fire watch (e.g. French Flag).

7.2.2.1.3 Type of fixed fire detection system

SOLAS II-2/20.4.1 requires a standard fixed fire detection and alarm system in line with FSS Code requirements. For practical purposes, it is worth noting that sample extraction smoke detection systems are not allowed on passenger ships vehicle spaces since SOLAS II-2/20.4.2 prohibits such systems[5] in “*open ro-ro spaces, open vehicle spaces and special category spaces*”. Therefore, this section focuses on fixed fire detection and fire alarm systems as described in FSS Code Chapter 9.

In addition, on passenger ships constructed on or after 2010, the system is to be addressable i.e. capable of identifying remotely and individually each detector and manually operated call point (FSS Code Ch. 9

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[5] Sample extraction smoke systems have been prohibited in SOLAS 1989 amendments (MSC.13(57)), applicable to ships constructed on or after 1 February 1992. As far as BV knows, this was a consequence of the bad service conditions observed on ro-ro ships for such systems (pipe ageing and corrosion) which usually had a common steel piping with the gas fire-extinguishing system.

§2.1.7). Before 2010, the fixed fire detection system was required to be divided into sections, and to be able to indicate in which section a detector has been activated.

7.2.2.1.4 Fire patrol

Efficient fire patrols are required as per SOLAS II-2/7.8 and SOLAS II-2/20.4.3.1. On passenger ships carrying more than 36 passengers, it is made clear that each member of the fire patrol is to be provided with a two-way portable radiotelephone apparatus, properly trained and familiar with the ship.

7.2.2.2 Performance

7.2.2.2.1 General

SOLAS II-2/20.4.1 sets the following general performance requirements:

- “The fixed fire detection system shall be capable of rapidly detecting the onset of fire”
- “After being installed, the system shall be tested under normal ventilation conditions and shall give an overall response time to the satisfaction of the Administration”

Common practice as per BV field experience is to perform this test using a smoke generator. A usual criterion is that the fire detection system is to be activated within 3 minutes.

A similar criterion can be found in French Flag Regulations (div 221-II-2/7.4) and BV Rules (NR467 Pt F, Ch. 3, Sec. 1 [3.2.15]) for unattended machinery spaces fire detection.

FSS Code Ch. 9 §2.1.2 lists the following main functionalities for the fire detection system:

- “control and monitor input signals from all connected fire and smoke detectors and manual call points;
- provide output signals to the navigation bridge, continuously manned central control station or onboard safety centre to notify the crew of fire and fault conditions;
- monitor power supplies and circuits necessary for the operation of the system for loss of power and fault conditions; and
- *the system may be arranged with output signals to other fire safety systems*” (communication, alarm and public address systems, ventilation, fire doors and fire dampers, fire extinguishing and systems supporting evacuation such as Low Location Lighting (LLL))

7.2.2.2.2 Maintenance

In-service testing and proper maintenance are required in FSS Ch. 9 §2.5.2, SOLAS II-2/7.3 & SOLAS II-2/14.2.2.

7.2.2.2.3 Alarm

The activation of any detector or manually operated call point is to initiate a visual and audible alarm at each indicating unit, i.e. at least at the safety centre and at the navigation bridge.

After 2 minutes, if the alarm has not been acknowledged, an audible fire alarm is to be automatically sounded throughout the crew accommodation and service spaces, control stations and machinery spaces of category A (FSS Ch. 9 §2.5.1).

In addition, a special alarm is required by SOLAS II-2/7.9.4, in order to allow summoning the crew from the navigation bridge or safety centre.

Sound pressure levels are given in FSS Ch. 9 §2.5.1.9.

7.2.2.2.4 Information exchange and interaction with other systems

In general, FSS Code Ch. 9 §2.1.3 limits the interaction of the fire detection system with other systems to output signals sent to other safety systems. It however allows the fire detection system to be connected to a decision management system[6] provided this decision management system can be disconnected without impact on the required functionalities for the fire detection system. It is also required that malfunction of the decision management system will not propagate into the fire detection system.

IACS UR E22 reckons the fire detection system as a category III, i.e. in case of fire, its failure could "*immediately lead to dangerous situations for human safety, safety of the vessel and/or threat to the environment*". It therefore sets a number of requirements for the system supporting software development and testing process, aiming at ensuring its operational reliability.

In addition, MSC.1/Circ.1430 makes it clear that the fire detection system may control the release of the water-based fixed fire-fighting system in the vehicle space, in case the fixed fire-extinguishing system is a manual deluge system, automatic deluge system or pre-action system[7].

7.2.2.3 System arrangement

7.2.2.3.1 Location of detectors

SOLAS II-2/20.4.1 clarifies that the "*spacing and location* [of the detectors] *shall* [… take] *into account the effects of ventilation and other relevant factors*". Further detail is provided in FSS Ch. 9 §2.4.2, together with a table summarizing the maximum spacing between detectors:

"*Detectors shall be located for optimum performance. Positions near beams and ventilation ducts, or other positions where patterns of air flow could adversely affect performance, and positions where impact or physical damage is likely, shall be avoided. Detectors shall be located on the overhead at a minimum distance of 0.5 m away from bulkheads, except in corridors, lockers and stairways.*"

Table 3: Spacing of detectors (FSS Ch. 9 Table 9.1)

Type of detector	Maximum floor area per detector (m^2)	Maximum distance apart between centres (m)	Maximum distance away from bulkheads (m)
Heat	37	9	4.5
Smoke	74	11	5.5

It is to be noted that FSS requirements for detector location are applicable for all kinds of spaces; they are not specific for ro-ro spaces. As a complement, in case the fixed fire extinguishing system is a manual deluge system, automatic deluge system or pre-action system, MSC.1/Circ.1430 makes it clear that:

- only smoke or heat detectors are allowed below hoistable ramps; and
- reduced spacing is to be considered for spot-type heat detectors where beams project more than 100 mm below the deck.

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[6] A decision management system refers to a system able to gather information from several other sub-systems such as ventilation, fire detection, fuel level, fire doors etc. and will support ship management for e.g.:

- Dealing with an emergency by displaying all relevant information on one terminal, helping identifying the emergency scenario and proposing detailed action lists to tackle the emergency
- Training by simulating emergencies
- Maintenance planning

[7] Other fixed fire extinguishing systems are wet pipe systems which include their own thermo-sensitive bulbs and will therefore not rely on a separate fixed fire detection system for activation.

7.2.2.3.2 Section arrangement

Fire detection sections are not allowed to cover more than one Main Vertical Zone (MVZ) (FSS Ch. 9 §2.4.1.4). In addition, a fire detection section covering a ro-ro space is to be separated from (FSS Ch. 9 §2.4.1.2):

- Control station
- Service spaces
- Accommodation spaces

For practical purposes, this means that ro-ro spaces are to be provided with dedicated fire detection sections, since ro-ro spaces generally are located in a dedicated Main Horizontal Zone. Only machinery spaces other than category A located in the same horizontal zone could be covered by the same detection section.

In addition, in case the fixed fire extinguishing system is a manual deluge system, automatic deluge system or pre-action system, MSC.1/Circ.1430 requires that fire detection sections be the same as the zones of the fixed fire-extinguishing system: "*The area of coverage of the detection system sections should correspond to the area of coverage of the extinguishing system sections.*"

For practical purposes, on addressable fire detection and fire alarm systems, several sections may be arranged in series on the same electrical cable and separated by suitably located isolators.

7.2.2.3.3 Cable routing

As a general rule, one single fire should not be able to damage a section in more than one location (FSS Ch. 9 §2.4.3.2, requirement for addressable systems) – i.e. the data highway should not pass more than once through a given space as per IACS UI SC117 – and no section should pass twice through a given space. When this cannot be avoided for very large spaces, the maximum possible distance between the two parts of the section is to be ensured (FSS Code Ch. 9 §2.1.6.4, requirement for addressable systems).

Cables are not to pass through spaces with high fire risk such as galleys and machinery spaces of category A, except for serving these spaces and when necessary for power connection (FSS Ch. 9 §2.4.3.1).

In addition, for ships submitted to Safe Return to Port (SRtP) regulations, i.e. ships having a length of 120 m or more or ships having 3 MVZ or more, the fire detection system is to remain operational after a fire or flooding casualty as per SOLAS II-2/21.4. For practical purposes, this generally implies:

- Redundant control panel and input/output cabinets and
- Redundant cable routing or using fire- and flooding-resistant cables[8]

(See SOLAS II-2/21.4 as interpreted by MSC.1/Circ.1369, MSC.1/Circ.1437 as well as NR598)

7.2.2.3.4 Monitoring and control

As a minimum, monitoring and/or control are to be available at the following locations:

- At the safety centre (control panel)
- At the navigation bridge (indicating unit capable of identifying which detector has been activated)

Monitoring and control requirements are summarized in the Table 4, in line with FSS Ch. 9 §2.5.1 and SOLAS II-2/7.9.2 & 7.9.3 requirements.

<u>System operating conditions:</u>

The control panel is to make a clear distinction between:

- Normal condition
- Fire alarm condition

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[8] Fire resistant cables to be tested according to IEC 60331-1 and 2
Flooding resistant cables to be provided with sheathing complying with IEC 60092-359

- Acknowledged alarm condition
- Electrical fault condition
- Silenced alarm condition
- The system is to reset automatically to normal operating conditions after all alarms and fault conditions are cleared

Table 4: Monitoring and control requirements

Monitoring and control		Control panel (Safety centre)	Indicating unit (Navigating bridge)	Other indicating unit
Fire detection	Fire alarm (See [7.2.2.2.3])	Visual and audible	Visual and audible	Visual and audible
	Means to acknowledge fire alarm	X (sounders may be manually silenced)		
	Monitoring and Control for: • Fire doors • Ventilation	X		
	Location of sections and spaces covered	X	X	X
Power supplies and electrical circuits necessary for detection system	Electrical fault alarm (distinct from fire alarm): • Single open or power break • Single ground fault • Single wire-to-wire fault	Visual and audible		
	Means to acknowledge electrical fault alarm	X		

7.2.2.4 *Fire detectors*

7.2.2.4.1 General

The fire detection system is to include fire detectors and manually operated call points.

FSS Code Ch. 9 §2.1.5: All components are to be qualified for operation in marine environment (standard requirements for electrical equipment onboard ships). In addition, fire detectors located in hazardous areas[9] are to be adequate for such use (FSS Ch. 9 §2.3.1.8).

7.2.2.4.2 Type of detectors

FSS Code allows "*Detectors […] operated by heat, smoke or other products of combustion, flame, or any combination of these factors.*" (FSS Ch. 9 §2.3.1.1)

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[9] For practical purposes, fire detectors installed in ro-ro spaces below the bulkhead deck are in Zone 1, others are in Zone 2, since fire detectors are fitted on the deckheads.

As a complement, in case the fixed fire-extinguishing system is a manual deluge system, automatic deluge system or pre-action system, MSC.1/Circ.1430 requires that two types of fire detectors be combined.

In addition, it may be noted that several Flag States and classification societies require smoke detectors exclusively or in combination with other detectors in ro-ro spaces. BV Rules require that smoke detectors are installed in ro-ro spaces (NR467 Pt C, Ch. 4, Sec. 12 [3.1.1]). Similar requirements are given by the US Coast Guard and the Swedish Flag. The MCA (UK Flag Administration) requires smoke detectors exclusively or a combination of smoke and flame detectors.

The requirement to have at least smoke detection in ro-ro spaces is based on the fact that smoke detection is considered as more reliable than standard flame or heat detectors. Standard heat or flame detectors are also considered less efficient in ro-ro spaces since:

- Heat sensors located on garage space deckhead were expected to result into quite long activation times due to deck height
- Flame detectors were expected to lead to a number of false alarms due to reflections etc.

7.2.2.4.3 Qualification and performance standards

In general, fire detectors are to be qualified according to EN 54:2001 and IEC 60092:504 (FSS Ch. 9 §2.3.1 and MSC/Circ.1035). Usual performance requirements are:

- For smoke detectors: Activation for 2% obscuration/m ≤ smoke density ≤ 12.5% obscuration/m

  “Smoke detectors […] shall be certified to operate before the smoke density exceeds 12.5% obscuration per metre, but not until the smoke density exceeds 2% obscuration per metre”

- Heat detectors: Activation when 54°C ≤ temperature ≤ 78°C (temperature increase rate ≤ 1°C/min)

  “Heat detectors shall be certified to operate before the temperature exceeds 78ºC but not until the temperature exceeds 54ºC”

- Carbon monoxide detectors: Alarm threshold set at 40ppm, sensitivity settings to be adjusted considering the fire hazard, likely source and risk of false alarm.

In addition, provisions are given for in service function testing (FSS Ch. 9 §2.3.1.6).

7.2.2.5 Electrical arrangement

7.2.2.5.1 System architecture

The system is to be organized into sections as per FSS Code Ch. 9 §2.1.4 and 2.4.1.1.

The first initiated fire alarm is not to prevent any other detector from initiating further fire alarms as per FSS Code Ch. 9 §2.1.6.3, applicable to addressable systems.

7.2.2.5.2 Components

- The control panel is to be tested according to standards EN 54-2:1997, EN 54-4:1997 and IEC 60092-504:2001 (FSS Ch. 9 §2.3.2)
- Cables are to be flame retardant as per IEC 60332-1 (FSS Ch. 9 §2.3.3)
- Cables routed through MVZ that they do not serve and cables to control panels in an unattended fire control station are to be fire resisting as per IEC 60331 (FSS Ch. 9 §2.3.3)

7.2.2.6 Sources of power

7.2.2.6.1 Continuous fire detection capability

The fixed fire detection and fire alarm system is to be fed from two sources of power with separate feeders, including an emergency source of power (FSS Code Ch. 9 §2.2.1). An emergency source of power has to comply with the requirements of SOLAS II-1/42 and 42-1 regarding location and autonomy. Especially, it has to be able to supply the fire detection system for 36 hours, after which it has to be capable of operating the fire alarm for 30min (FSS Ch. 9 §2.2.4). It is either the ship emergency generator (+ transitional source of emergency power) or dedicated accumulator batteries (FSS Ch. 9 §2.2.4 & 2.2.5).

An automatic change-over switch is to be provided to manage the transition between the main and emergency source of power, and a fault should not lead to the loss of both power supplies.

No temporary loss of the fire detection capability due to this change-over switch is accepted. In addition, a transitional battery may be required if the temporary loss of power can damage the fire detection system as per FSS Ch. 9. §2.2.2.

Although the alarm sounder is not formally required to be part of the fire detection system, IACS UI SC35 makes it clear that it is to be powered from a main and emergency source of power and from the transitional source of emergency power where required.

7.2.2.6.1.1 Sizing of the source of power

The power supply is to be sufficient for operation with 100 detectors activated, or all detectors provided onboard if this number is lower than 100 (FSS Ch. 9 §2.2.3).

7.2.2.6.2 Consequences of a fault

After an electrical fault or electrical failure:

- Identification capability is to be kept in the whole section, except for the faulty detector (FSS Code Ch. 9 §2.1.6.1, applicable to addressable systems)
- The initial configuration is to be restored (FSS Code Ch. 9 §2.1.6.2, applicable to addressable systems)

7.2.2.6.3 Temporary disconnection

FSS Code Ch. 9 §2.1.1 allows temporary disconnection of the fire detectors in ro-ro spaces during loading and off-loading, provided:

- Detectors in other spaces remain operational
- Fire patrol is maintained in the ro-ro space while the detectors are disconnected
- The detectors are automatically re-connected after a pre-set duration

MCA (UK Flag Administration) clarify in their guidance that:

- Manual call points and manual release mechanisms may not be disconnected
- The duration of the timer is to be adapted to the time of loading/unloading
- The central unit is to indicate whether the detector sections are disconnected or not

7.3 Current practices related to detection

7.3.1 *Review of current practices in location of openings and detectors*

7.3.1.1 Detector locations

According to regulations (as outlined in paragraph 7.2.2.3.1), vehicle spaces, ro-ro spaces and special category spaces shall be equipped with a fixed fire detection and fire alarm system complying with the FSS Code (in special category spaces the detection system may be replaced by an “efficient fire patrol system”) (SOLAS II-2/20.4). Sample extraction smoke detection systems are only allowed to replace a point smoke or heat detection system in closed vehicle and closed ro-ro spaces, i.e. not in spaces to which passengers have access and hence they are not very common on ro-ro passenger ships.

The FSS Code stipulates that, with regard to positioning of the detectors, they shall be located for “optimum performance” (FSS Ch. 9 §2.4.2). Position close to beams and ventilation ducts where patterns of airflow could adversely affect the performance should be avoided and the minimum distance to any bulkheads shall be 0.5 m. Positions where impact or physical damage is likely should also be avoided. The maximum spacing of detectors was highlighted in Table 3, but the Administration may require or permit different spacing than those specified in the table if justifiable based on test data which show the characteristics of the detectors.

The current practices are to use smoke detectors or combined smoke and heat detectors rather than heat detectors only. The detectors are seen most often to be positioned between ceiling beams close to the lower edge of the beams, see Figure 6, which results in good protection against physical impacts and possibility of early detection in combination with high ventilation. In case of high airflow, the smoke will be carried along the airflow below the beams rather than accumulate in between the ceiling beams at an early stage of a fire. Without or with low airflow, it may be more beneficial to position the detectors close to the ceiling. However, with detectors not present between all beams, the response time may vary substantially depending on fire location. For the specific case in Figure 6, it would probably be better with some greater distance to the nearest beam. However, it is more important to keep distance to transverse beams than to longitudinal beams relative to the airflow.

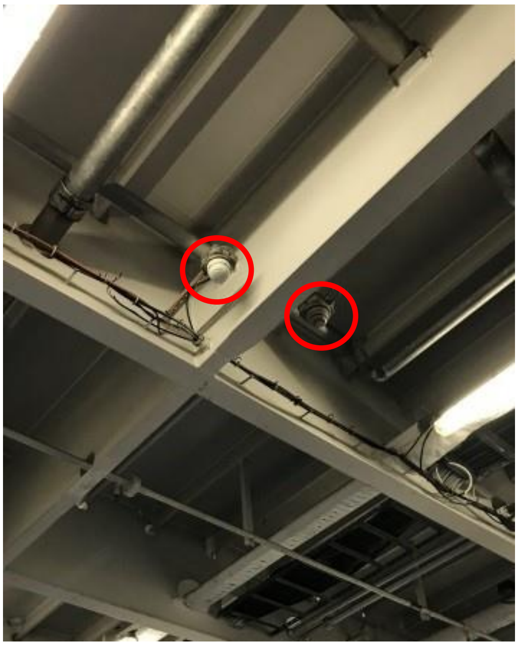

Figure 6: Point detectors locations (new and old detectors)

The maximum allowed distance between detectors is primarily limited by the maximum floor area coverage per detector. For evenly distributed smoke detectors, the maximum distance is 8.6 m rather than 11 m, as visualized in Figure 7. However, for unevenly distributed detectors, the maximum distance of 11 m must be taken into account, as illustrated to the right side in Figure 7. A spot-check on a ro-ro passenger ship in Gothenburg showed an estimated distance of about 7 m between most detectors and in the public report on the fire safety approach in DESSO ROPAX (Arvidson, Axelsson, Simonson, & Tuovinen, 2006), a maximum coverage area of 25 m^2 was recommended for combined smoke and heat detectors, i.e. significantly less than the prescribed 37 m^2 (heat detectors) and 74 m^2 (smoke detectors). It seems that some safety margin to the prescribed values is often used, which of course could be a conscious decision to attain a higher safety level.

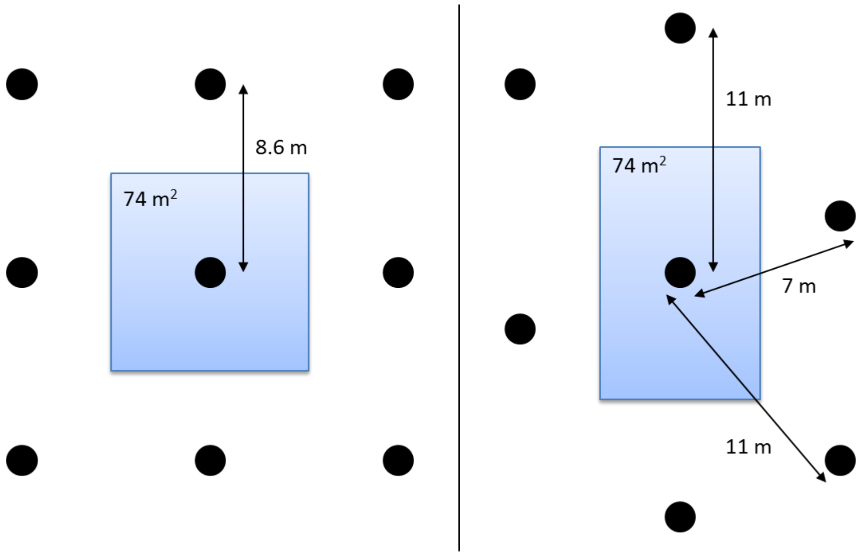

Figure 7: Detector spacing illustrations

For sample extraction smoke detection, the FSS Code stipulates that the “smoke accumulators shall be located for optimum performance and shall be spaced so that no part of the overhead deck area is more than 12 m measured horizontally from an accumulator” (FSS Ch. 10 §2.3.1.2). Smoke accumulators are assumed to be sampling holes where the smoke enters the sampling pipes connected to the detector unit. Referring to Figure 8, it is seen that the coverage area of an accumulator can be 288 m^2, which is substantially more than what is allowed for point smoke detectors. However, these systems are also required to be more sensitive than point smoke detectors (alarm activation at smoke obscuration below 6.65% per metre instead of 12.5% per metre). Nevertheless, several sampling holes on the same sampling pipe may dilute the smoke, which is why a more sensitive detector unit could be needed to achieve a sensitivity corresponding to a point smoke detector. The regulation does not allow more than four accumulators connected to the same detection unit (FSS Ch. 10 §2.3.1.4).

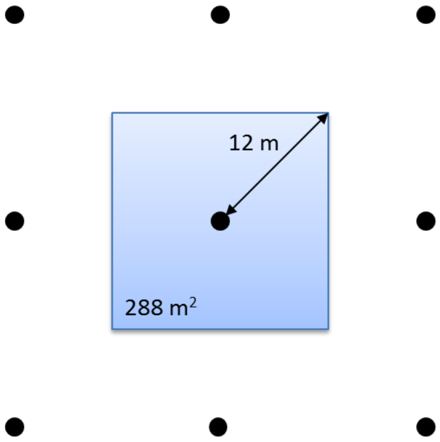

Figure 8: Sampling holes (accumulators) spacing. Regulation prescribes that only four accumulators can be connected to the same detection unit

It seems that regulations are less stringent for sample extraction smoke detection with regard to response time, which could be one reason why these systems are not allowed to replace point detection on most ro-ro passenger ships. Another reason might be that ageing and corrosion problems have been reported for these systems when the same metal pipes as for extinguishing systems have been used. In other applications, sample extraction smoke detection is considered a good option in case early detection is important, especially in combination with high airflow. That is the reason why these systems are common in e.g. data centres and air ducts. An experimental study on fire detection in buses show that for the tested systems, sample extraction systems are less sensitive to high airflow at the position of the detector/sampling hole (Willstrand, Brandt, & Svensson, 2016).

Another aspect is that the FSS Code specifies that the sampling pipe arrangements shall be such that the location of the fire can be readily identified (FSS Ch. 10 §2.3.2.1). To address the fire location, separate sampling pipes would be needed to cover specific areas. There are systems that allow complex pipe networks to be connected to one detection unit, giving multiple addressable zones for one detection system. It is also possible to address the fire location by changing the pipe flow direction at an alarm. After purging the pipes, the flow direction is changed again, and by measuring the time until smoke is again detected the system can identify where the smoke enters the pipes.

Although sample extraction smoke detection is not common on ro-ro passenger ships due to regulations, they are sometimes used. DNV-GL has studied 35 fires within ro-ro spaces between 2005 and 2016 and out of 10 cases with reliable data for detection, there was one case where the fire was detected by a sample extraction smoke detection system. In 8 cases there was a fixed fire detection system (assumed to be smoke detection) and in one case there was no fixed fire detection system (weather deck). (DNV-GL, 2016)

Other types of detectors are sometimes used as complement to the required detection systems. For example in the DESSO ROPAX project (Arvidson, Axelsson, Simonson, & Tuovinen, 2006), a gas sampling system was recommended to be fitted in ro-ro spaces in order to detect fumes from gasoline or diesel oil leaking from the vehicles on deck. One can assume that gas detection systems may be more common in the future due to an increased number of alternative fuel vehicles. Gases that are relevant to detect are e.g. methane (CNG and LNG vehicles), propane/butane (LPG vehicles), hydrogen (fuel cell vehicles) and combustible gases from battery ventilation (electric and hybrid vehicles).

There is normally no fixed fire detection system on weather decks (no requirements in regulations), but accident reports have highlighted the problem. Flame detectors are used on some ships, as seen in Figure 9. Other means of fire detection on weather decks are watchmen, fire patrols and CCTV cameras (used for surveillance with no fire detection algorithms).

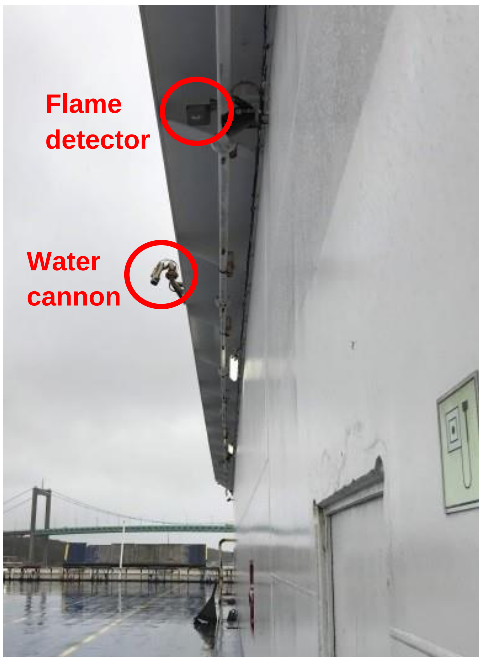

Figure 9: Weather deck on Stena Germanica

7.3.2 *Review of different system set-ups*

According to the FSS Code, a fixed fire detection and fire alarm system shall not be used for any other purpose, except that closing of fire doors and similar function may be permitted at the control panel (FSS Ch. 9 §2.1.2). At least two power sources shall exist to power electrical equipment used for the system. (FSS Ch. 9 §2.2).

Normally detectors are required to be activated by heat or smoke, but activation by other signatures may be considered by the Administration, provided that the detectors are not less sensitive than detectors activated by heat or smoke. Flame detectors shall only be used in addition to smoke or heat detectors (FSS Ch. 9 §2.3.1.1). All detectors should be of a type such that they can be tested for correct operation and restored to normal surveillance without the renewal of any component (FSS Ch. 9 §2.3.1.5).

As mentioned in section 7.2.2.4, current practice is to use smoke detectors or combined smoke and heat detectors rather than heat detectors only. Combined smoke and heat detectors seem to be common today since it is quite easy to update existing smoke detector systems into a system using combined point smoke/heat detectors. Heat detection is considered important for monitoring fire development and fire spread, which is not possible with only smoke detection. When the fire increases, the smoke detectors will be saturated and smoke will be detected far from the fire origin, but with heat detectors it is easier to estimate the fire size and fire spread. Another benefit of using heat detection is that heat detection is more resistant to false alarms, which means that heat detection can be activated during loading and discharging of ro-ro spaces. It is current practice and acknowledged to inactivate smoke detectors during loading and discharging. However, the FSS Code requires that detectors in other spaces remain operational and that a fire patrol is maintained in the ro-ro space while the detectors are disconnected. Furthermore, the detectors need to be automatically reconnected after a pre-set duration time. A timer, normally located at the bridge, is used to reconnect the fire detection system automatically if reconnection is not made manually. An example of such a timer can be seen in Figure 10. This timer allows two hours to pass before automatic reconnection, but it is preferable to use shorter pre-set durations.

Figure 10: Timer (2 h) for inactivation and reconnection of fire detection system on (all) ro-ro spaces

The FSS Code also prescribes that activation of any detector or any manually operated call point shall start an audible and visual fire signal at the control panel and indicate the activated unit. If the signals have not received attention within two minutes, an audible alarm shall be automatically sounded in the crew accommodation, service spaces, control stations and machinery spaces. The control panel can be located either on the bridge or in a continuously manned central control station. Indicating units, showing the section of the activated detector and the location of the different sections, shall be easily accessible to responsible crew members.

Figure 11 shows an example of different monitors situated at the fire detection system control panel. Upon alarm, the upper monitor shows the activated detector unit(s). Any CCTV camera covering the area is automatically displayed on the monitor in the lower right corner of the photo. This is not required but can assist decision-making. The control panel will also give an audible and visual false signal in case of power loss or failure in electric circuits for the detection system, as required by the FSS Code.

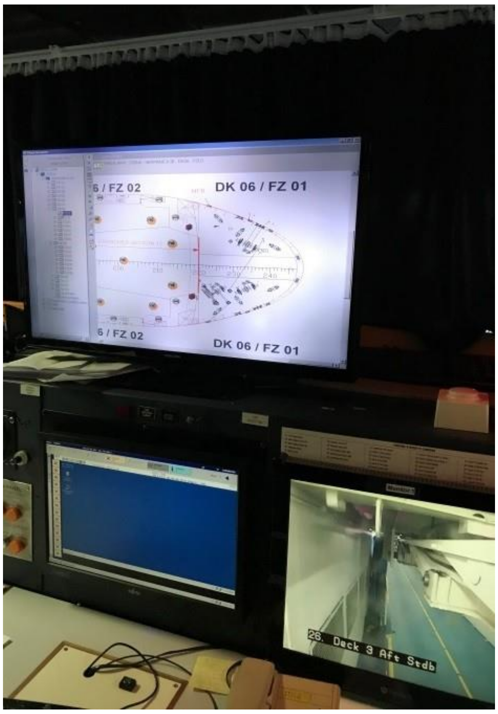

Figure 11: Example photo of different monitors at the fire detection system control panel

7.4 Literature Review Decision-Making

Decision-making research has been developing steadily from the middle of the 20th century, starting with applications in the economical sciences, later developing in parallel to safety research and its focus on decision-making in natural environments. While early models of decision-making were based on logic, viewing humans as purely rational, probabilistic agents or “homo economicus” (Simon, 1955), research in experimental psychology during the 1970’s came to suggest that human problem-solving and decision-making cannot simply be modelled upon logical “machine” behaviour.

This development was headed by researchers Daniel Kahneman and Amos Tversky (Tversky, 1974) who demonstrated that in experiments, participants applied mental heuristics or “rules-of-thumb” when solving problems involving probabilities, something that was connected to systematic errors in judgment (i.e. “cognitive bias”). Participants tended to ignore probability features such as sample size and regression toward the mean, they typically had vague and often faulty conceptions around chance, and they tended to anchor probabilistic judgments to other numbers arbitrarily present in the test environment. At the same time, even when participants were made aware of such typical errors, they tended to have a strong confidence in their own judgments. Kahneman and Tversky concluded that mental rules-of-thumb often lead to severe and systematic errors in decision-making.

7.4.1 *Development towards Naturalistic Decision-Making*

Research around cognitive bias came into question during the 1980’s when studies on decision-making took a turn towards naturalistic environments and skilled decision-makers. Global and industrial developments during the late part of the 20th century had given rise to a new strain of decision-making research focused on professional activities in safety-critical environments such as fire-fighting, nuclear and military operations (Endsley M. H., 2007). Even though these environments were essentially different, studies revealed similar traits in professional decision-making. Furthermore, while the behaviour of these decision-makers did not conform with rational models, neither did it reflect the large propensity for error suggested by research in experimental psychology. It was pointed out that previous research had been carried out with the expressed purpose of exposing weakness and errors in decision-making. Moreover, experiments carried out by Kahneman and Tversky (Tversky, 1974) had taken place in laboratory environments and participants were most often recruited from the student body. For professionals working in natural-environments, even though single decisions could be biased, reduced cognitive effort and speed overweighed inherent weaknesses in the process, particularly in high-stakes time-critical situations (Cohen, in Klein, Orasanu, Calderwood, & Zsambok, 1993).

Different models have been suggested to represent a continuum for human thought and decision-making, ranging from quick "intuitive" decisions to slow and deliberate "rational" thinking. One example is Jens Rasmussen's division in skill-based, rule-based and knowledge-based behaviour (Rasmussen, 1986) representing different levels of conscious control, where each respective level has its own application depending on the familiarity of the experienced situation. Another model is suggested by Hammond (Hammond, 1980) who showed that professional decision-makers tend to move between analytical reasoning and snap judgments based on feedback from the environment, e.g. if the task is ill-structured or well-structured, so that the situation at hand induces a certain decision-making process (Klein, Orasanu, Calderwood, & Zsambok, 1993).

Research concerned with professional activities in natural environments came to be known as "Naturalistic Decision-Making" (NDM) (Klein G. , Naturalistic Decision-making, Human Factors, 2008) and during the following decades NDM developed in different directions representing different aspects of decision-making such as Recognition-Primed Decision-Making (RPD) (Klein G. , Sources of power: How people make decisions., 1998), Situation Awareness (SA) (Endsley M. , 1995), Sensemaking (Weick, 1995) and Common Operational Picture (COP) (Lass, Regli, Kaplan, Mitkus, & Sim, 2008). Later developments have seen a distinct shift towards a "systems perspective" on safety-critical operations (Wilson, 2014) with an emphasis on system interactions, also factoring in aspects such as cultural influences.

7.4.2 *Recognition-Primed Decision-Making*

In one of his papers (Klein G. , Sources of power: How people make decisions., 1998), Gary Klein (one of the foreground figures of NDM) notes that the greatest challenge for decision-makers in professional settings is not choosing between alternatives but making sense of events and conditions. The inherent uncertainty of real-world operations means that pre-written rules and procedures will never provide all the information necessary, and instead, situational interpretations made by the decision-maker will have a heavy impact on outcomes.

Through studies of persons involved in fire-fighting command (Klein, Orasanu, Calderwood, & Zsambok, 1993), Klein demonstrated that a large portion of decision-making in this context was concerned with situation recognition, where the decision-maker classifies the situation as typical or atypical based on pattern matching. When determining how to respond, the decision-maker will evaluate options serially (but often semi-consciously). Because of the nature of neural activation and human memory, the first element in the "cognitive action queue" will be the most typical response to the perceived situation, and professional experience will increase the likelihood of this perception being correct. After selecting a potential response, the decision-maker will simulate possible outcomes of the action mentally. RPD is described by Klein as a combination of intuition and analysis where intuition is understood as recognition (Kahneman & Klein, 2009), while mental simulation involves more of analytical reasoning. This means that professionals employ both kinds of processes to reach a balance between speed and analytical depth, something that has also been demonstrated in the maritime domain (Harvey, Zheng, & Stanton, 2013). It has later been observed that recognition-oriented strategies are more pronounced for experienced persons while novices rely more on deliberate analysis (Klein, et al., 2003). Professional intuition develops if the environment is sufficiently stable and provides enough grounds for predictions (Kahneman & Klein, 2009).

The fact that professional decision-making relies so heavily on the interpretation and recognition of typical situations has introduced another shift in decision-making research, moving from the individual decision-maker to focus more on his or her environment and, particularly, the aspects of that environment that may facilitate or obstruct interpretation. Even though experience is invaluable for effective decision-making, the environment and its artefacts as well as collaborative conditions also have to provide the right support (Van Santen, Jonker, & Wijngaards, 2009).

7.4.3 *Situation Awareness*

Situation Awareness (SA) is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future (Endsley M.

, 1995). This process, named Endsley stresses, depends both on stable cognitive properties and on experience, preconceptions and goals. The concept of Situation Awareness has developed in parallel to research on RPD and has had a profound impact on both safety research and safety management during the last decades.

Since its early conceptualisation, the subject of Situation Awareness has developed into more fine-grained models highlighting different aspects of acquiring SA, for example (Jungert, Hallberg, & Hunstad, 2006) the division in *Organizational Awareness* (the understanding of available resources and their possible use), *System Awareness* (knowledge about supportive technology), *Environmental Awareness* (knowledge about contextual factors and risks) and *Activity Awareness* (actions and intents of people working around the operator). The concept of Activity Awareness reflects the observation in SA research that Situation Awareness is often created jointly among different actors involved in a work process, and that it relies heavily on communication, sharing of information and the creation of shared interpretations (Comfort, 2007). The concept of SA has also been applied in maritime domain safety research (Cordon, Mestre, & Walliser, 2017).

The idea that SA is often created jointly, in a team of human operators, is also reflected in Mental Models research which stresses the collaborative nature of emergency-related decision-making. Mental models can be formed around equipment and tools used by a team, the work that is to be accomplished including goals, requirements and problems, the characteristics of the team including knowledge, beliefs and skills, and around what work processes are appropriate and effective. The extent to which these models are shared by team members can strongly affect the chances for effective teamwork (Van Santen, Jonker, & Wijngaards, 2009). The way that knowledge of the situation is represented in the environment (information artefacts in a Command and Control Centre for instance) was explored under the heading of Common Operational Picture (COP) (Norros, et al., 2009).

7.4.4 *Decision-making and Context*

Research describes Naturalistic Decision-Making as a process of intense interaction between the decision-maker and her environment, where manipulations of that environment can have drastic effects on emergency outcomes. In a study directed towards platform supply vessels, Sandhåland *et al.* (Sandhåland, Oltedal, Hystad, & Eid, 2015) compile a number of aspects ranging from the individual, to the group, to more abstract phenomena that may all affect the timeliness and precision of decision-making.

Early research cited in the previous chapter illustrated the impact of the decision-maker’s individual properties – that he or she typically needs a large amount of experience to be able to assess the situation and predict possible developments. Even with experience, however, distractions in the environment such as noise, communications or movement can put a strain on the decision-maker’s attention, with negative effects for all of the phases of SA acquirement. The impact of direct environmental factors can also be aggravated by stress (Gok & Atsan, 2016), sleep disruption and fatigue (Sneddon, Mearns, & Flin, 2013). Furthermore, in the design sciences it is well known that the way a person perceives and solves a problem is heavily influenced by both system design and interface design. Even though the decision-maker is competent, well-rested and the environment is relatively calm, flaws in the way information is gathered, integrated, presented and shared can still introduce errors (Endsley M. R., 2012).

On the team level it was observed that communication is vital to uphold a common understanding of the problem at hand, and that activities such as joint planning may serve to reinforce shared perceptions. At the same time, although it is widely recognised that coordination within a team is important for SA, researchers have also pointed out that a completely shared SA may not always be beneficial. Team members possess different roles and because of that they may need to interpret and use information differently. Furthermore, the fact that conceptions are shared within a group does not need to say anything about their validity. A team may fall into groupthink, where the will to maintain consensus prevents critical thinking (Njå & Rake, 2009), meaning that opposing facts and interpretations can also be viewed as an asset in situations of uncertainty. The fact that decision-making is also affected by social dynamics is explored by Van Santen *et al*. (Van Santen, Jonker, & Wijngaards, 2009), who conclude that the construction of sound, shared mental models is helped by features in the organisation such as wide-spread experience, shared ownership within the group, mutual respect, self-evaluation/self-correction and frequent chances to work in self-managing teams.

7.4.5 *A Systems Perspective on Fire Incident Decision-Making*

Decision-making is a process affected by context – by the individual professional, her profile and background experience, by surrounding artefacts such as information systems, tools and environments, by interactions and relations including teamwork and cultural or social dynamics, and by the extended system such as the overall organisation, law, regulations and economic pressures (Hetherington, Flin, & Mearns, 2006). It would however be wrong to draw the conclusion that because of this context-dependency, human decision-making is bound to be biased. Instead, it appears that the human capacity to draw on many different (and often incomplete) sources of information and to relate them to environmental dynamics is precisely what enables good outcomes.

In cognitive science, human thinking has for long been treated as a distributed phenomenon (Hutchins, 1995) where the individual, together with his or her manipulation of the environment (and the resulting representations in the environment) are seen as one compound cognitive system. The observation that Situation Awareness in a complex environment tends to be distributed over several people and technical artefacts has led to an expansion of the SA concept (i.e. DSA (Parisi & Lüdtke, 2016)). This implies that studies of decision-making must apply a systemic perspective, looking to the whole system in order to understand the performance of the individual. On the other hand, research shows that in safety matters it is common to address individual system components in isolation, without consideration to how their functionality depends on the people and technology surrounding them (Santos-Reyes & Beard, 2001).

Work on a ship is a complex system, resting on a high level of experience, skill and collaboration, involving the use of specialised equipment, tools and procedures (Sandhåland, Oltedal, Hystad, & Eid, 2015). A rapidly evolving fire scenario will often mean a sharp increase in many of the factors that are known to undermine decision-making, such as workload and noise. This will place high demands on the system, ranging from the individual crewmember, to all the different aspects of the immediate environment, to the interplay within the extended system on-board (e.g. between the bridge and ro-ro spaces), to outer layers of the system such as the land organisation, nearby ships and other relevant parties (e.g. Vessel Traffic Service (VTS)). All of these aspects, activities and environments represent concrete design cases that could be explored for their ability to support decision-making in the case of an on-board fire.

7.5 Generic ships

7.5.1 *Identification of types and sizes of ro-ro passenger ships*

7.5.1.1 Purpose and Method

For the purpose of making the study in FIRESAFE II applicable to a vast part of the world fleet of RoPax, ships were grouped by the following parameters:

- Passenger capacity;
- Lane metre capacity[10];
- Cargo deck type (closed, open, weather or a combination); and
- Size of weather deck (if any).

In order to assess the relevancy of the grouping, it was crosschecked with the Stena fleet of 29 RoPaxes and with data from a world fleet database. When crosschecking with the Stena fleet, type of trade or usage of the ship in a fleet network was also considered. After grouping the ships according to above parameters and the description here, this was checked against a ratio between lane metre and passenger number (LM/Pax ratio). This ratio was proven to match the grouping to a large extent and it is believed it can be used as a key figure when grouping the world fleet.

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[10] Lane metre capacity should be used with great care when considering the world fleet as the measure can differ between operators. Figures used in this report were provided by EMSA.

7.5.1.2 Grouping

Four clear groups emerged: *Ferry RoPax*, *Large RoPax*, *Standard RoPax*, and *Cargo RoPax*. These groups are described in detail in Table 5.

Table 5: Typical description of the main groups

<table>
<tr><td colspan="5">Figures below on passenger capacity and lane metre capacity are examples picked from the Stena fleet cross check and shall be seen as examples only.
For world fleet grouping LM/Pax ratio is used.</td></tr>
<tr><th></th><th><i>Ferry RoPax</i></th><th><i>Large RoPax</i></th><th><i>Standard RoPax</i></th><th><i>Cargo RoPax</i></th></tr>
<tr><td>General description</td><td>RoPax or Ferry with focus on carriage of passengers but which can also carry cargo similar to a <i>Standard RoPax</i>.</td><td>RoPax with focus on carriage of cargo and of passengers.
High lane metre capacity</td><td>RoPax with focus on carriage of cargo and of passengers.
Standard lane metre capacity.</td><td>RoPax with focus on carriage of cargo.</td></tr>
<tr><td>Passenger capacity</td><td>900-2 300</td><td>600-1 500</td><td>900-1400</td><td>Just enough to carry the number of drivers necessary to load the ro-ro spaces with accompanied trailers. Less than 400.</td></tr>
<tr><td>Lane metre capacity</td><td>1 000-2 300 m</td><td>Above 3 000 m</td><td>1 000-2 300 m</td><td>1 000-2 300 m</td></tr>
<tr><td>Deck type</td><td>Only closed ro-ro spaces or mainly closed ro-ro spaces and a small weather deck.</td><td>All three types of ro-ro spaces: closed ro-ro spaces, open ro-ro spaces and weather deck. The size of weather deck is generally medium to large within this category.</td><td>All three types of ro-ro spaces: closed ro-ro spaces, open ro-ro spaces and weather deck. The size of weather deck is generally medium to large within this category.</td><td>Closed ro-ro spaces and large weather decks.</td></tr>
<tr><td>LM/Passenger</td><td>Less than 2</td><td>2-7</td><td>2-7</td><td>More than 7</td></tr>
<tr><td>Visualization</td><td>Stena Superfast</td><td>Stena Scandinavica or Hollandica</td><td>Stena Flavia or Mersey</td><td>Stena Gothica</td></tr>
<tr><td>Final Grouping</td><td><i>Ferry RoPax</i></td><td colspan="2"><i>Standard RoPax</i></td><td><i>Cargo RoPax</i></td></tr>
</table>

7.5.1.3 FIRESAFE II groups

For the purpose of this study, it was decided to merge *Large RoPaxes* and *Standard RoPaxes*. For trade and usage within a fleet network, the difference between the two groups is acknowledged. This is mainly due to the different harbour arrangements required to accommodate very large ships.

However, there are also several similarities and the total number of *Large RoPaxes* is low. Therefore, the the LM/Pax ratio was retained as the only grouping criteria. Most of the *Large RoPaxes* were merged with *Standard RoPax* and formed the final group *Standard RoPax*.

Therefore, the vessels were grouped using the ratio LM/Pax for grouping. The lane metre to passenger ratio categorized according to the FIRESAFE II Group on the Stena fleet is provided in Figure 12.

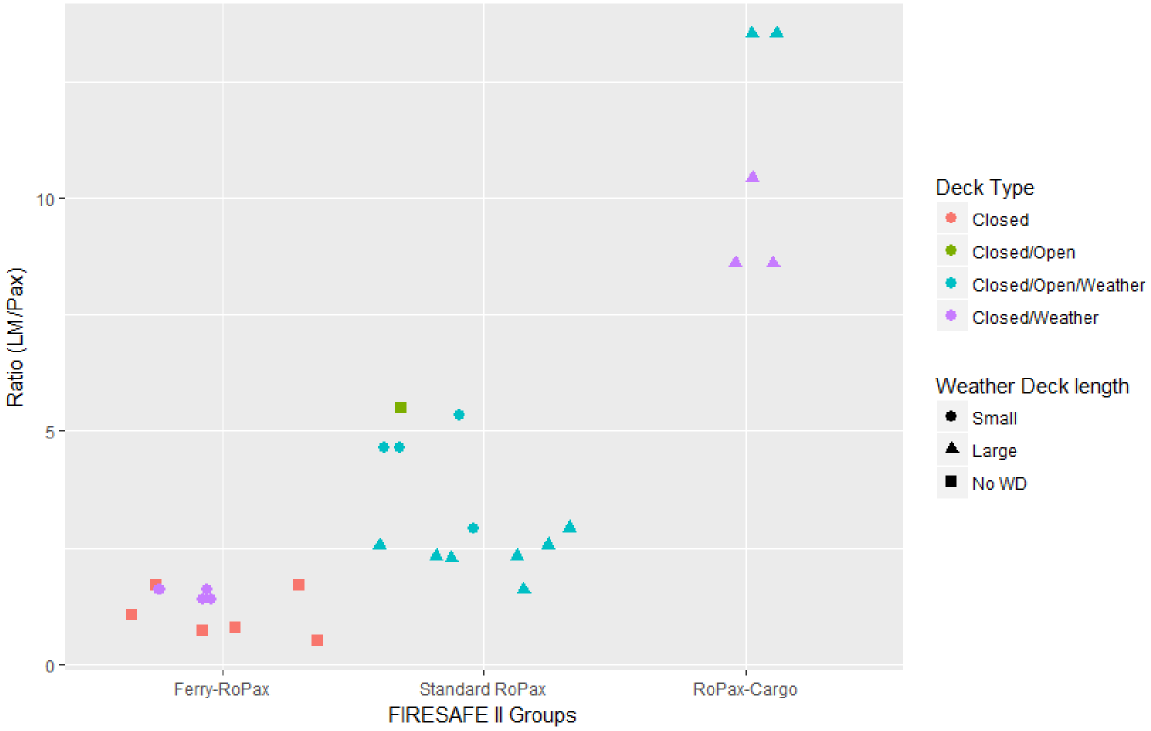

Figure 12: Lane metre to passenger ratio categorized according to the FIRESAFE II Group on the Stena fleet

Not all ships of the FIRESAFE II fleet match all the criteria but the definition can be taken as a guideline. The distribution of the FIRESAFE II fleet (in black) and of the Stena fleet (in colour) in terms of lane metre capacity and number of passengers is provided in Figure 13 along with the borders of the FIRESAFE II groups (red lines). The large circles represent the Stena ships selected as generic ships.

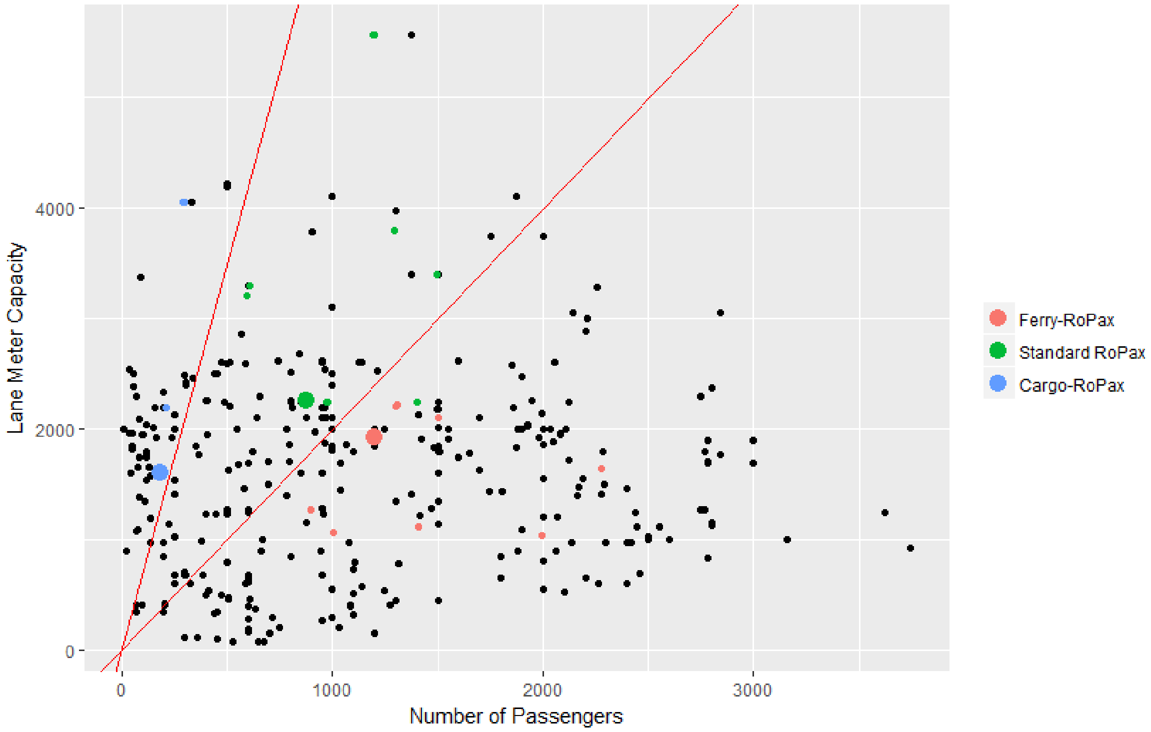

Figure 13: Lane metre capacity vs. number of passengers for the FIRESAFE II fleet (in black) and the Stena fleet (in colour) and FIRESAFE II groups (red lines)

7.5.2 *Description of the generic ships chosen for the study*

7.5.2.1 Cargo RoPax

This sample ship is a representative design of a *Cargo RoPax* of a size of 13 294 GT. It was designed with a capacity of 186 persons onboard. The vessel is compliant with all relevant international rules and regulations. The ship is designed to SOLAS A.265 and later reconstructed to operate as per the SOLAS 90. Ship has 6 MVZs.

Passenger cabins are located in the superstructure on Decks 4, 5 and 6. Restaurant is located on Deck 6. The remaining part of Deck 4 consists of a garage and weather deck. Deck 2 is the main deck with ro-ro lanes throughout the full length of the ship. Lower hold on Deck 1 is for trailers and trucks. Picture of this ship is provided in Figure 14.

The total ro-ro area (excluding casings etc.) on the *Cargo RoPax* is 4 364 m². 67% of this area is located in closed spaces (lower hold, main deck and garage), the remaining 33% being the weather deck.

Figure 14: Picture of the Stena Gothica (*Cargo RoPax* ship)

The main characteristics of the *Cargo RoPax* ship are detailed in Table 6 and the cargo decks particulars are further described in Table 7.

Table 6: Main characteristics of the *Cargo RoPax* ship

GENERAL	*Cargo RoPax*
Length overall	171,05 m
Breath moulded	20,25 m
Draught	5,27 m
Built	1982
Deadweight	4 750 t
Gross tonnage	13 294 t
Net tonnage	3 988 t
Cargo capacity	1 600 lm
Pax capacity	186 pax
Route	Göteborg - Frederikhamn, day and night
Passage time	3,5 hrs
Fire pump 1	71 m³/h
Fire pump 2	70 m³/h
Emergency fire pump	90 m³/h
Drencher pump	288 m³/h

Table 7: Description of the cargo decks of the *Cargo RoPax* ship

General description	**Weather deck (+ garage), deck 4**
Extinguish	Drencher (garage) Fire monitors (WD)
Detection	Heat detectors (garage)
Containment	WD + garage with open aft
Ventilation	Mechanical
Cargo	Standard trailers/trucks
General description	**Main Deck, deck 2**
Extinguish	Drencher
Detection	Smoke detectors + Heat detectors (Heat det. in drencher section 6, ships length extended)
Containment	Closed ro-ro space
Ventilation	Mechanical
Cargo	Standard trailers/trucks
General description	**Lower Hold, deck 1**
Extinguish	Drencher
Detection	Smoke detectors
Containment	Closed ro-ro space
Ventilation	Mechanical
Cargo	Standard trailers/trucks

7.5.2.2 *Standard RoPax*

This sample ship is a common and popular design of a RoPax of a size of 26 904 GT. It was designed for with a capacity of more than 880 persons onboard. The vessel is compliant with all relevant international rules and regulations. The ship is designed to and operating as per the SOLAS, 1974. Ship has 6 MVZ.

Passenger cabins are located in the superstructure on Deck 6, above the restaurant on Deck 5. The remaining part of Deck 5 consists of a weather deck for cars. Below on Deck 4 is located an open ro-ro space with a small weather deck in the aft. Deck 3 is the main deck with ro-ro lanes throughout the full length of the ship. A small car deck seldom used (about 82 cars) is located on Deck 2 and some 250 lane metres for trailers and trucks are situated in the lower hold on Deck 1. Picture of the ship is provided in Figure 15.

The total ro-ro area (excluding casings etc.) on the *Standard RoPax* is 9 446m². The repartition between the different ro-ro spaces is as follows: 53% of closed spaces (lower hold, main deck and car deck), 32% of open spaces (garage) and 5% of weather deck.

Figure 15: Picture of the Stena Flavia (*Standard RoPax ship)*

The main characteristics of the *Standard RoPax* ship are detailed in Table 8 and the cargo decks particulars are further described in Table 9.

Table 8: Main characteristics of the *Standard RoPax* ship

GENERAL	*Standard RoPax*
Length overall	186,5 m
Breath moulded	25,5 m
Draught	6,16 m
Built	2008
Deadweight	5 875 t
Gross tonnage	26 904 t
Net tonnage	8 912 t
Cargo capacity	2 200 lm
Pax capacity	830 pax
Route	Nynäshamn - Ventspils, day and night
Passage time	6-9 hrs, pending timetable
Fire pump 1	110 m^3/h
Fire pump 2	n/a
Emergency fire pump	110 m^3/h
Drencher pump	960 m^3/h

Table 9: Description of the cargo decks of the *Standard RoPax* ship

<table>
<tr><td>General description</td><td colspan="3">Weather Deck for cars, deck 5</td></tr>
<tr><td>Extinguish</td><td colspan="3">None</td></tr>
<tr><td>Detection</td><td colspan="3">None</td></tr>
<tr><td>Containment</td><td colspan="3">Weather deck</td></tr>
<tr><td>Ventilation</td><td colspan="3">None</td></tr>
<tr><td>Cargo</td><td colspan="3">Standard cars, minivans</td></tr>
<tr><td>General description</td><td colspan="3">Open ro-ro space/Weather Deck, deck 4</td></tr>
<tr><td>Extinguish</td><td colspan="3">Drencher (except for WD part)</td></tr>
<tr><td>Detection</td><td colspan="3">Smoke detectors (except for WD part)</td></tr>
<tr><td>Containment</td><td colspan="3">Open ro-ro space, side openings >10%, open aft towards small WD and ramp</td></tr>
<tr><td>Ventilation</td><td colspan="3">Natural + partly mechanical</td></tr>
<tr><td>Cargo</td><td colspan="3">Standard trailers/trucks</td></tr>
<tr><td>General description</td><td colspan="3">Main Deck, deck 3</td></tr>
<tr><td>Extinguish</td><td colspan="3">Drencher</td></tr>
<tr><td>Detection</td><td colspan="3">Smoke detectors</td></tr>
<tr><td>Containment</td><td colspan="3">Closed ro-ro space</td></tr>
<tr><td>Ventilation</td><td colspan="3">Mechanical</td></tr>
<tr><td>Cargo</td><td colspan="3">Standard trailers/trucks, Various ro-ro units</td></tr>
<tr><td>General description</td><td>Lower Hold, deck 1</td><td>General description</td><td>Car Deck in lower hold, deck 2</td></tr>
<tr><td>Extinguish</td><td>Drencher</td><td>Extinguish</td><td>Drencher</td></tr>
<tr><td>Detection</td><td>Smoke detectors</td><td>Detection</td><td>Smoke detectors</td></tr>
<tr><td>Containment</td><td>Closed ro-ro space</td><td>Containment</td><td>Closed ro-ro space</td></tr>
<tr><td>Ventilation</td><td>Mechanical</td><td>Ventilation</td><td>Mechanical</td></tr>
<tr><td>Cargo</td><td>Standard trailers/trucks</td><td>Cargo</td><td>Standard cars</td></tr>
</table>

7.5.2.3 Ferry RoPax

This sample ship is a common and popular design of a *Ferry RoPax* of a size of 30 285 GT. It was designed for with a capacity of more than 1 200 persons onboard. The vessel is compliant with all relevant international rules and regulations. The ship is designed to and operating as per the SOLAS 1997 including Stockholm Agreement. Ship has 5 MVZs.

Passenger cabins are located in the superstructure on Deck 8, above the restaurant on Deck 7. The remaining part of decks 7 and 8 consists of decks for engine casing, life boats and rafts. Below on Deck 5/6 is located a closed ro-ro space with open end to a small weather deck in the aft. Deck 3 is the main deck with ro-ro lanes throughout the full length of the ship. A small car deck is located on Deck 2 and cars and vans are stowed in the lower hold on Deck 1. Picture of the ship is provided in Figure 16.

The total ro-ro area (excluding casings etc.) on the *Standard RoPax* is 9 446m². The repartition between the different ro-ro spaces is as follows: 53% of closed spaces (lower hold, main deck and car deck), 32% of open spaces (garage) and 5% of weather deck.

Figure 16: Picture of the Stena Superfast VIII (*Ferry RoPax* ship)

The main characteristics of the *Ferry RoPax* ship are detailed in Table 10 and the cargo decks particulars are further described in Table 11.

Table 10: Main characteristics of the *Ferry RoPax* ship

GENERAL	*Ferry RoPax*
Length overall	203,3 m
Breath moulded	25 m
Draught	6,6 m
Built	2001
Deadweight	5 920 t
Gross tonnage	30 285 t
Net tonnage	10 703 t
Cargo capacity	1 900 lm
Pax capacity	1 200 pax
Route	Belfast - Cairnryan, day and night
Passage time	2,5-3 hrs, pending timetable
Fire pump 1	150 m^3/h
Fire pump 2	n/a
Emergency fire pump	150 m^3/ h
Drencher pump	285 m^3/h

Table 11: Description of the cargo decks of the *Ferry RoPax* ship

<table>
<tr><td>General description</td><td colspan="3">Cargo Deck, deck 5</td></tr>
<tr><td>Extinguish</td><td colspan="3">Drencher (except for WD part)</td></tr>
<tr><td>Detection</td><td colspan="3">Smoke/heat detector (except for WD part)</td></tr>
<tr><td>Containment</td><td colspan="3">Closed ro-ro space with open aft towards small WD</td></tr>
<tr><td>Ventilation</td><td colspan="3">Mechanical</td></tr>
<tr><td>Cargo</td><td colspan="3">This deck has 4 lanes which can take high freight traffic full 50% of crossings, the 2 outside lanes normally have drop trailers or cars.</td></tr>
<tr><td>General description</td><td colspan="3">Main Deck, deck 3</td></tr>
<tr><td>Extinguish</td><td colspan="3">Drencher</td></tr>
<tr><td>Detection</td><td colspan="3">Smoke/heat detector</td></tr>
<tr><td>Containment</td><td colspan="3">Closed ro-ro space</td></tr>
<tr><td>Ventilation</td><td colspan="3">Mechanical</td></tr>
<tr><td>Cargo</td><td colspan="3">Mix of running freight traffic and drop trailers. Cars/vans on busy trips.</td></tr>
<tr><td>General description</td><td>Lower Hold, deck 1</td><td>General description</td><td>Car Deck in lower hold, deck 2</td></tr>
<tr><td>Extinguish</td><td>Drencher</td><td>Extinguish</td><td>Drencher</td></tr>
<tr><td>Detection</td><td>Smoke detectors</td><td>Detection</td><td>Smoke detectors</td></tr>
<tr><td>Containment</td><td>Closed ro-ro space</td><td>Containment</td><td>Closed ro-ro space</td></tr>
<tr><td>Ventilation</td><td>Mechanical</td><td>Ventilation</td><td>Mechanical</td></tr>
<tr><td>Cargo</td><td>Cars, vans.</td><td>Cargo</td><td>Cars, vans</td></tr>
</table>

8 HAZARD IDENTIFICATION

8.1 Analysis of casualty data

8.1.1 *Source of data*

The dataset used in this study was provided by EMSA. No other sources of data were used.

8.1.2 *Fires in ro-ro spaces*

Taking into account the slight change in the fleet considered and the experience gained since FIRESAFE, casualty data analyses was updated with 2016 casualty data.

8.1.2.1 Proportion of fires in ro-ro spaces

From 2002 to 2016, 132 fires were recorded[11], and among 30% of them (37 accidents) originated in a ro-ro space. This result is highly consistent with the findings from FIRESAFE.

8.1.2.2 Frequency of fires

Over the 15 year-period, the 37 fires in ro-ro spaces recorded lead to an average of 2.5 accidents[12] per year.

Taking into account the exposure time calculated in Section 7.1.2.1 (7 001 shipyears between 2002 and 2016), the 15-year average accident frequency was estimated to 5.28E-03 fires in ro-ro spaces per shipyear ($CI_{90\%}$ [3.72E-03; 7.28E-03]).

This average accident frequency is close to the one estimated in FIRESAFE: 5.79E-03 fatalities per shipyear.

The annual accident frequency of fires in ro-ro spaces is shown in Figure 17.

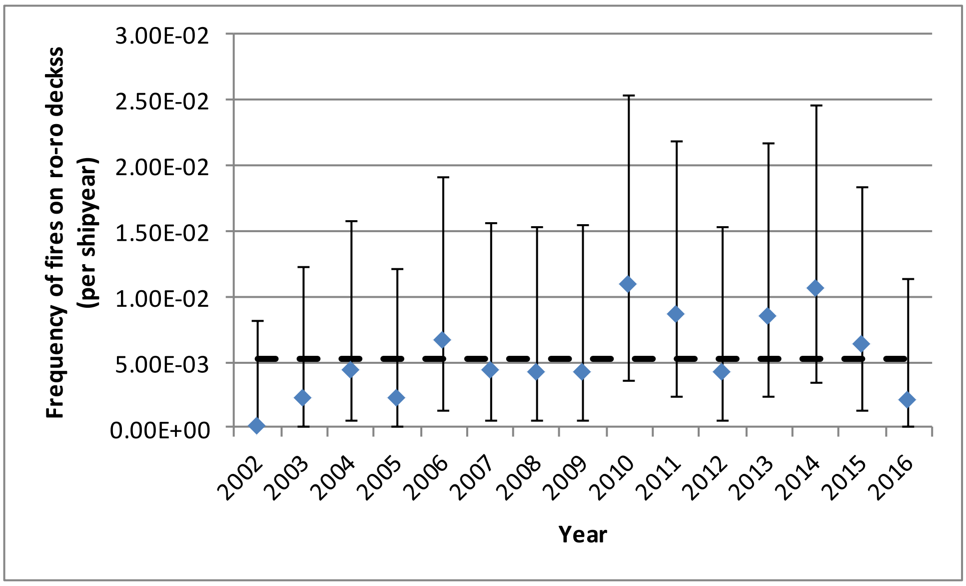

Figure 17: Annual accident frequency of fires in ro-ro spaces with 90% confidence interval between 2002 and 2016 and the 15-year average

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[11] Unless explicitly stated otherwise, this means “recorded in the database provided by EMSA”.

[12] In the following, unless explicitly stated otherwise, “accident” means “fire in ro-ro spaces”.

8.1.2.3 Total losses, fatal accidents

Over the period 2002-2016, 4 ships were reported as Total Losses (either constructive or actual) due to a fire in ro-ro spaces. These are the Al Salam Boccaccio 98 in 2006, the Lisco Gloria in 2010, the Norman Atlantic in 2014, and the Sorrento in 2015.

Over the same period, there were 2 fatal accidents recorded in the database. The M/V Al Salam Boccaccio 98, causing 1 031 fatalities and missing, and Norman Atlantic with 18 fatalities and missing. This led to a Potential Loss of Life (PLL) of 1.50E-01 fatalities per shipyear.

This PLL is significantly different from the one estimated in FIRESAFE ($PLL_{FIRESAFE}$ = 8.14E-3 fat/shipyear). This is due to the fact that the Al Salam Boccaccio 98 was excluded from the FIRESAFE fleet (due to her keel laid date).

It is to be noted that one accident (named "Accident B" in FIRESAFE) was removed from the dataset considered in FIRESAFE II due to a misleading categorization of the class society of this ship in the database used in the first study).

8.1.2.4 Impact of ship age

The accident frequency per age at date of incident as shown in Figure 18 was estimated by normalizing the number of accidents for each age categories with the exposure time. As in the first study, it can be seen that a potential impact of ship age on the accident frequency cannot be ascertained.

It was shown in FIRESAFE that 90% of the fires in ro-ro spaces were originating from the cargo itself which could explain this finding.

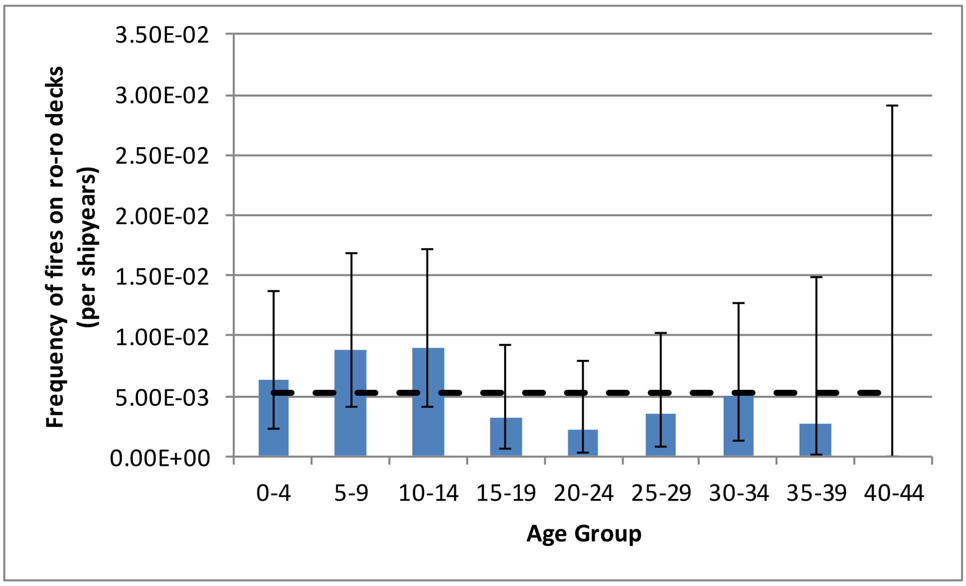

Figure 18: Accident frequency per age at date of incident and 90% confidence interval and average for the whole fleet at risk over the period 2002-2016

8.1.2.5 Impact of ship size

Figure 19 shows the impact of ship size on the accident frequency on the FIRESAFE II fleet over the period 2002-2016.

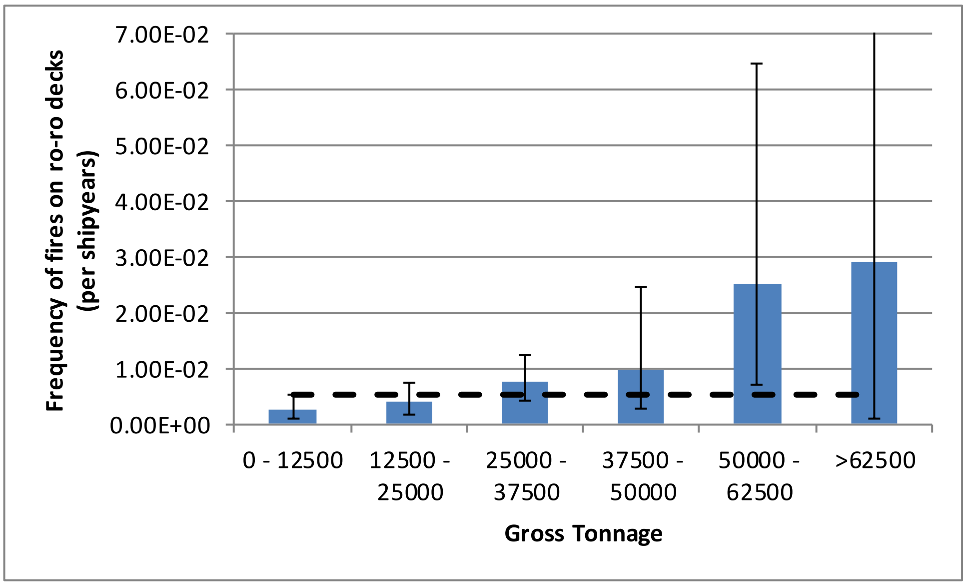

Figure 19: Frequency of fires in ro-ro spaces per size (GT) with 90% confidence interval between 2002 and 2015 and average for all categories

There seems to be an increasing trend for larger ships, as indicated in Figure 19. However, it must be noted that the number of shipyears for the size category (GT > 62 500) is very low (about 35 shipyears over the full period) to provide an accurate estimation of the accident frequency for that period, as clearly shown by the large confidence interval.

The confidence interval for the GT > 62 500 size segment was cut short to maintain the readability of the figure, the upper bound being at 2.6E-01 fires in ro-ro spaces per shipyear.

As mentioned during the analysis of the impact of ship age on the accident frequency, and based on the review of the accident reports, sources of most of the fires in ro-ro spaces were external to the ship itself, i.e. mainly due to cargo.

8.2 Hazard Identification – Detection

8.2.1 Review of accident investigation reports

A review of available literature (accident investigation reports, press clippings, IMO documents and presentations from accident investigation bodies) was done with a specific focus on detection and decision, to extract relevant data and trends from accidents that have materialized in the past.

Documentation for a total of 24 accidents was investigated and for which 18 cases accident investigation reports were available. Each report summarizes the development of the accident as well as recommendations. The retrieved data and the common specifics for the accidents were grouped from a detection perspective, as elaborated below.

8.2.1.1 Detection of fire by the dedicated system: type of activated detectors

In the studied accidents, different combinations of heat and smoke detection systems were used on the ships: heat and smoke, only heat or only smoke.

The review of the accident reports showed that the detectors that detected the fire were in most cases smoke detectors.

In further detail, the Al Salam Boccaccio 98 investigation report from Panama (Panamá Maritime Authority) states that the presence of smoke detectors could have detected the fire earlier, while the Amorella accident investigation report (Onnettomuustutkintakeskus, 2005) mentions only smoke detectors detected fire while heat detectors did not give any alarm at the initial stage.

Several accident investigation reports emphasised the benefits of having both types of detectors installed on board. In the above-mentioned Amorella report, it is stated that "because of different fire types, each type of detector is necessary". The Commission in charge of the investigation of the Stena Spirit fire (Bahamas Maritime Authority, 2017) also states that "installation of only smoke detectors […] (no heat or flame detectors installed), although this is not required by the rules, could contribute to the delay in activation of the fire alarm."

None of the reports mentioned the use of the CCTV as a means for detection. However, CCTV has sometimes been used in the confirmation phase, once fire has been detected (see section 8.3.1).

8.2.1.2 Detection of fire manually (by passenger or crew)[13]

In some cases, detection of the fire was reported by a crew member and sometimes shortly before the fixed detection system, as in the Lisco Gloria fire. In this case the AB, during his inspection of the garage area, noticed the smell of burning (Danish Maritime Accident Investigation Board, 2014). Some fires have also been detected by chance (i.e. not in the context of a fire patrol) as was the case for the URD fire. Two crew members, randomly passing the main car deck, discovered a fire on top of a lorry (German Federal Bureau of Maritime Casualty Investigation and Lithuanian Maritime Safety Administration, 2012). No reported cases where passengers have detected a fire were found, which may result from the fact that passengers are prohibited in most ro-ro spaces during voyage.

8.2.1.3 Issues with detection

In some reports, issues with fire detection are reported. Some commonly reported issues are presented below.

8.2.1.3.1 Internal failure

A detection issue during the accident on the Pearl of Scandinavia may be seen as an internal failure of the fire detection system, as the detection system was rebooted without effect. Another internal failure happened for the Norman Atlantic (press articles and public presentation during the Group of Expert at EMSA, 2017) when the alarm panel went faulty.

In the accident on the Commodore Clipper, the alarm also stopped working properly, and the detection system was subsequently rebooted and silenced many times and eventually ceased to function. It should be noted that in the case of the Commodore Clipper, the detection system had been incorrectly installed, probably during construction, with isolating devices in the wrong locations. This allowed high voltages from other damaged cables to enter the fire detection network, overloading the control circuits and shutting down the whole system. The consequences of the fire detection system failing particularly early during the incident were significant

8.2.1.3.2 External causes

Another explanation to detection failure is external causes, such as openings or ventilation of the ro-ro space. This can cause delay in the detection of the fire (Norman Atlantic and Sorrento, press articles) or indicate the wrong location of fire (Al Salam Boccaccio 98).

The Norman Atlantic accident investigation report illustrates the combined effects of the internal failure and external causes: "The fire was detected by sensors belatedly, due to the technical issues described before, with particular reference to the presence of side openings, which, combined with the wind blowing in that area, enabled fire to develop so much that, when it was finally detected, it could no longer be kept under control." (DIGIFEMA, 2018).

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[13] As this review is mainly based on accident investigation reports, it is very likely that this type of detection is not well represented in this sample. Fires detected early by the crew are likely dealt with manually, without the activation of the fixed extinguishing system, and very likely without causing significant consequences or requiring an accident investigation.

The positioning of the detectors was also mentioned as a probable cause of their operation failure for the Stena Spirit fire (Bahamas Maritime Authority, 2017).

8.2.1.3.3 Manual detection fire

The fire patrols may fail due to a too low frequency of patrols, as in the Kriti II fire during which “the patrol system in the garages, carried out with a view to early detection of a fire, did not perform as expected, since the interval between two successive checks was not sufficient to detect the occurrence and development of the fire” (Hellenic Bureau for Marine Casualties Investigation, 2014). Other accident investigation reports also described events in which the fire had started and grown between two rounds of fire patrols. However, it should be noted (further described in section 10.5.5 Increased frequency of fire patrols) that even high frequency fire patrols may not be sufficient in case of a quick fire development.

8.2.1.4 Accident investigation reports recommendations

Out of all the recommendations for safety improvements in the 18 accident investigation reports reviewed, only two recommendations specifically target fire detection:

- Addition of smoke detectors where only heat detectors are installed already; and
- Direct link between the detection system and the drencher system, allowing automatic system activation.

8.2.2 Fire Detection Hazard Identification workshop

A Hazard Identification (HazId) workshop was held at RISE in Borås, 29 November 2017. A Fire HazId workshop is a systematic brainstorming session carried out by a multidisciplinary design team, to investigate the fire safety of a specific subject. The selected participants should mirror the diversity of the subject in the sense that they should possess all the necessary competence to identify potential hazards and risk control measures for the specific subject. The focus of this HazId was “fire detection in ro-ro spaces” and the experts gathered are presented in Annex A1.13, along with their expertise in particularly design, fire safety, human factors, risk analysis, operation and regulations for ro-ro passenger ships.

8.2.2.1 Method

A spreadsheet was developed prior to the HazId workshop, to guide the procedure and for documentation of results. The spreadsheet and the HazId procedure was based on a Failure Mode and Effects Analysis (FMEA) risk analysis procedure, which is commonly used in risk management.

Initially in the workshop, different means for detection were identified as:

- Fixed smoke/heat detection;
- Detection by fire patrol;
- Manual crew/passenger detection and alarm through call point;
- Manual crew/passenger detection and alarm through radio; and
- CCTV not dedicated to detection.

Before starting to identify failure modes for each means of detection, and to assist in this process, the desired functions and affecting conditions were identified for the means of detection. Thereafter, ship conditions, systems, procedures etc. were considered to identify failure modes and resulting effects of failure. These were divided into the three types of ro-ro spaces, namely closed ro-ro space, open ro-ro space and weather deck. Associated risk control measures were also identified in relation to each failure mode and significant related comments were noted. This procedure was repeated for each means for detection, as long as failure modes could be identified, and then for the other means for detection.

Furthermore, prior to the FIRESAFE II study, a more extensive Fire HazId workshop with a more general focus on “ro-ro space fire safety” was commercially organized for Stena by RISE Fire Research in 2015. Participants in that HazId workshop were four research scientists with expertise in risk management, fire safety engineering, fire hazard identification, vehicle fire cause investigation, maritime regulations, ship fire safety and ship surveying, as well as nine senior officers and fleet managers (masters, chief engineers and naval architect) selected for their competence and interest in RoPax fire safety issues. The results from that Fire HazId were not made publicly available but by acceptance from Stena, the results related to detection were used to complement the results of the workshop organized within FIRESAFE II. Identified hazards and proposed RCMs from other projects were also incorporated as appropriate and the participants were also given the opportunity to make post-HazId additions.

8.2.2.2 Results

The resulting tabulation of fire detection hazards and risk control measures is documented in Annex A1.1.

Some notable results from the workshop were:

- The detection system is often deactivated during loading and discharging as well as during maintenance operations. This often implies deactivation of many or all ro-ro spaces;
- It is difficult to detect a fire at its early stage of development if the fire develops inside cargo or a vehicle;
- The environment in ro-ro spaces is quite harsh, and it is not uncommon that dirt, salt, exhaust fumes etc. clog the detectors;
- The detection system alarm panel can be illogical (confusion regarding the detection frame number, detection section, drencher section, CCTV numbering, etc.) which could imply delayed first response and delayed extinguishing system activation;
- No detection system is required for weather deck;
- The frequency of fire patrols is undefined and generally quite low;
- The accessibility within ro-ro spaces is very limited, which makes manual detection and fire localization difficult; and
- Many false alarms reduce the motivation of crew to quickly attend to alarms.

8.3 Hazard Identification – Decision

8.3.1 *Review of accident investigation reports*

Comparing the different accident investigations, it is clear that methodology and investigator competence greatly affect the depth and diversity of information attained. Some investigations provide ample information spanning from the individual to the organizational and the technical while others mainly include technical analyses. It is acknowledged within accident investigation research that “What You Look For Is What You Find” (WYLFIWYF), meaning that the preconceptions and special interests of the investigating team will influence what information is observed and ultimately included in the accident report. It is also acknowledged that “What You Find Is What You Fix” (WYFIWYF) (Lundberg, Rollenhagen, & Hollnagel, 2009). Limitations in the methodology and competence applied in investigations will eventually also limit what kinds of improvements can be made in the light of lessons learned. Negative events in socio-technical systems (systems comprised of technology and people working in organizations) are typically caused by a combination of many different actions, events and latent conditions. Because of that, improvements following on negative events must be equally diverse. Moreover, investigations based on a thorough understanding of operational conditions and limitations will also reduce the risk that interventions do not come in conflict with operational needs and provide some safeguard against unrealistic demands. In order to increase learning from events, different ways of increasing investigator competence and methodology could be explored.

8.3.1.1 Detection

From the reviewed analyses, it is apparent that the speed of detection will have a heavy impact of the success of response activities. In several of the incidents, the fire was discovered by members of the crew passing by the location by chance. On a number of occasions, these discoveries were made well before any reaction by technical detection systems. In the case of the Commodore Clipper, the first alarm triggered by the fire was electrical and was interpreted as a technical malfunction by the crew.

8.3.1.2 Localisation

In a number of cases, fire localization was obstructed due to design factors such as section markings that were unclear or hidden in smoke, poor accessibility, malfunctions in the fire alarm system or that the alarm system provided misleading or imprecise information. One such case is the Pearl of Scandinavia where fire spread, unclear alarm information and obstructed visibility caused an erroneous interpretation of the origin of the fire, creating false grounds for decision-making and delaying response. On the Joseph and Clara Smallwood a watchman was able to localise the fire, but because he received no feedback when pulling the nearest fire alarm switch, the watchman commenced to another location pulling yet another switch, possibly creating confusing around the actual location of the fire.

8.3.1.3 Situation Assessment

The early deployment of a runner to the fire scene, e.g. as seen in the case of the Pearl of Scandinavia, seems to offer advantages both for speed of assessment and first response. Despite this, situation assessment (e.g. the condition, spread and damage cause by the fire) proved a great challenge in all of the reviewed incidents. Some problems arose from issues in the interface between crew present at the fire scene and decision-makers on the bridge. This is commented on further in the section dealing with Communication. On the other hand it is sometimes noted that the assessment capabilities of crew members on-site has been crucial for decision-making. In several cases, situation assessment was also heavily influenced by poor accessibility caused by tight stowage and smoke. On several occasions, problems with situation assessment produced delays in decision-making that allowed the fire to develop further.

On several occasions, poor accessibility has essentially made the fire a black box and decisions have been made mainly based on information about temperature development in different parts of the ship. In these situations, technical artefacts such as heat cameras have been important for situation assessment, although a simple checking with the hand against bulkheads has also allowed crew members to gauge the development of the fire. CCTV assessment was attempted in most incidents (e.g. Commodore Clipper (Marine Accident Investigation Branch, 2011), Pearl of Scandinavia" (Danish Maritime Accident Investigation Board, 2011)) but has primarily offered confirmation of fire (e.g. cameras blocked by smoke). There is one mention of cargo documents being used for situation assessment (Stena Urd), although in this instance the documents did not contain all the information about the cargo necessary for assessment.

While several accident investigation bodies recommended to install CCTV (e.g. following the Und Adriyatik accident (IMO, 2012)), the Commission investigating the Stena Spirit incident (Bahamas Maritime Authority, 2017) "is of the opinion that the ship procedures should include an obligation to regularly check the CCTV camera images after activation of any significant alarm, including fire alarm."

8.3.1.4 Activation of drencher system

Not all investigations provide detailed information about the circumstances surrounding the activation of the drencher system. The investigation of the Stena Urd fire is one exception. Here, quick activation of the drenchers is attributed to crew training, experience and their in-depth knowledge of the ship.

There are several examples of situations where design flaws in environments, interfaces or equipment connected have introduced delays in drencher decision-making and activation. These flaws include insufficient or obstructed section markings provoking a kind of trial-and-error in drencher activation, illogical ship layout drawings in the drencher room that all the components (e.g. pumps) required for drencher activation have not been located in the drencher room and impaired valve operation due to stiffness. In the case of the Lisco Gloria, the drencher pump was set in manual mode in the engine control room and could not be started from the drencher control station, a fact that was not apparent for the crew members present.

It is apparent from these investigations that drencher activation is often associated with negative side effects that can both delay fire extinguishment and create operational hazards. The primary challenge is to handle the large quantities of water on deck created by the drenchers. Water outlets will often become blocked by debris from the fire. This may force the captain to make trade-off decisions. One such case is the Commodore Clipper where the drencher had to be run in intervals in order to maintain stability of the ship. In this case, it is noted that the officers lacked a way of calculating how much water could be accumulated without losing stability. There are also examples of creative ways of draining drencher water, for example using the ballast system to heel the ship allowing the water to escape. On the Al Salaam Boccaccio, however, attempts to use the ballast system for this purpose ultimately led to the sinking of the ship. Furthermore, there are several examples showing that the drencher system may have limited effect on the fire, primarily because the fire is shielded from the water by cargo or trailer tarps, but in some cases simply because the fire has spread too much for the drencher system to be efficient.

8.3.1.5 Manual Response

In several of the reviewed incidents, fire started in cargo deck environments with very limited access both for confirmation and fire response. Efficient stowage allows cargo capacity to be maximised, but at the same time makes it harder for fire response teams to reach the fire seat carrying heavy and cumbersome equipment, in particular the pressurised hose. In several instances, such as with the Joseph and Clara Smallwood, it was not possible to completely put the fire out until the ship had docked and several vehicles had been removed from the deck. It is also common that both situation assessment and fire response is inhibited by smoke at the deck, despite the use of Breathing Apparatus (BA) equipment.

Past incidents provide several examples of decisions surrounding ship operations that are made in order to inhibit an ongoing fire. This includes different ways of manoeuvring cargo deck fans for different purposes such as removing smoke, avoiding vacuum effects or to inhibit fire growth. Another common example is to alter the ship's course in order to direct smoke away from crew/passenger areas or to enable manual fire response. It is also apparent that some operational scenarios, such as berthing with an ongoing fire onboard, create serious challenges for crew resource management.

8.3.1.6 Communication

On the one hand, the response to an onboard fire demands that crew members and officers fulfil different functions at different locations on the ship. On the other hand, they must also work jointly, sharing information and collaborating to reach common goals. For officers on the bridge, problems with communication can undermine their situation awareness and have negative effects on decision-making. The reviewed incidents provide a number of examples of factors that may inhibit communication. The most common of those factors is malfunctions or reduced functionality in technical communication equipment, such as poor audio quality or insufficient coverage, requiring the coordinating person to move around and thus losing precious time. There are also examples of environmental factors inhibiting communication, such as noise or loud alarm signals. Communication may be impaired further because of language barriers within the crew. When audibility is limited, personnel may resort to common native languages, although this may reduce the ability of crew members with other nationalities to overhear and make use of shared information. Moreover, although social dynamics are rarely mentioned in investigations, there is mention of situations where an informal culture between crew and officers has promoted open dialogue, improving information-sharing and collaboration.

8.3.2 Decision-Making Hazard Identification workshop

A Hazard Identification (HazId) workshop was held at RISE in Borås, 29 November 2017. A HazId workshop is a systematic brainstorming session carried out by a multidisciplinary design team, to investigate the safety of a specific subject. The selected participants should mirror the diversity of the subject in the sense that they should possess all the necessary competence to identify potential hazards and risk control measures for the specific subject. The focus of this HazId was "Decision-making after a fire in a ro-ro space" and the experts gathered are presented in Annex A1.14, along with their expertise in particularly design, fire safety, human factors, risk analysis, operation and regulations for ro-ro passenger ships.

8.3.2.1 Method

Prior to the workshop, FIRESAFE II researchers had built a preliminary model of the phases and actors involved in fire incident decision-making. The first objective of the HazId was to correct and complement this model based on the expertise of the participants. Corrections resulted in the following sequence of operational phases, some of which are explained further within parentheses:

1. Bridge Response (The very first decisions following upon a fire alarm);
2. Verification (confirmation of whether there is an actual fire);
3. CCC Formation (Gathering the relevant personnel on the bridge);
4. “What to do” (Situation assessment before selection of response);
5. Systems activation (of drencher system, CO2 system or other);
6. Fire Squad Activation (Mustering and preparations);
7. Manual Fire-fighting;
8. Control (Fire evolution assessment).

The ensuing HazId work process consisted of an assessment of each phase for:

1. Relevant actors;
2. Important decisions;
3. Preconditions for correct and effective decision-making;
4. Potential hazards in relation to a particular decision;
5. Possible preventive measures.

As a reference to widen the scope of discussions, a large-scale printout had been prepared displaying “Common Performance Conditions” i.e. factors that are known from Human Factors research to have an impact on operations in safety-critical environments. Results from the HazId were used in two ways, first as a basis for observations carried out on-board a Swedish RoPax ship, second as a foundation for the fault trees developed later in the study.

8.3.2.2 Results

Data collected during the HazId on fire incident decision-making reveals a system composed of many different actors, using numerous types of tools, equipment and environments, constrained by a large number of contextual conditions. Building Situation Awareness around a developing fire may often be challenging, in part due to the typical ro-ro space environment with tightly-packed cargo and a lack of information (e.g. concerning vehicle properties), a situation that will often be aggravated by problems with equipment and practices for communication. Furthermore, many decisions that may appear straightforward (such as the deployment of crew and extinguishing systems activation) may actually be associated with additional risks, and it was agreed that decision-making and action in this context requires a well-developed combination of both fire-specific and domain-general knowledge (i.e. seamanship, work experience). Participants also pointed out that the decision-making process will probably be affected by local conditions, involving technical and organisational as well as cultural aspects (e.g. hierarchy or “blame culture”). To properly assess decision-making risks in ro-ro space fire incidents, this diversity across the world fleet (and even within the same shipping company) must be acknowledged.

The complete results of the Decision-Making HazId can be seen in the Annex A1.2. Some notable results from the hazard identification were:

- Alarm system management (e.g. information presentation, coherence, noise levels);
- Runner deployment (e.g. speed of deployment);
- Way finding, localisation and relevant support (e.g. familiarity, markings, signage);
- Assembly of key decision-makers (e.g. availability);
- Resource management on the bridge (e.g. competing goals/processes, fire management in relation to regular operations);
- Drencher activation mandate (including hierarchy, blame culture);
- Assessment of fire characteristics, environment and fire spread;
- Ventilation management (smoke removal vs. supply of more oxygen to the fire);
- Maintenance of knowledge and competence (e.g. realism in training); and
- Communication issues (between bridge, fire scene, drencher station, engine room).

9 RISK ANALYSIS

9.1 Background

The purpose of the risk analysis in step 2 of the FSA process, as described in MSC-MEPC.2/Circ.12/Rev.2, is to undertake a detailed investigation of the frequencies and consequences of identified accident scenarios.

This is achieved by using suitable risk models built by means of standard techniques such as fault trees and event trees. The generic methodology applied during risk analysis consists of linking fault trees with the event trees to represent full accident scenarios.

This methodology was acknowledged in document III 3/4/5 (IMO, 2016) and was used in the FIRESAFE study where risk models (one event tree and two “fault trees”) were developed to investigate the topics *Electrical Fires as ignition risk* and *Fire Extinguishing Failure*.

In particular, the main fire risk model (event tree) identified the pivotal events which affect the outcome of different fire scenarios in ro-ro spaces and had been developed in such a way that it could be used in future investigations into specific nodes beyond the scope of the first FIRESAFE study.

Means for early detection as well as the decision making and operations involved in extinguishing system activation were not investigated in detail in FIRESAFE. These aspects were then assessed and considered in the same node of the risk model, namely early decision for activation. However, in this study, the node was analytically investigated and separated into its two main components, detection and decision.

This led to the development of a formal definition of what was considered as an early or late detection, as described in Section 9.2.

Based on these definitions and prior to the in-depth analysis of detection and decision failures, a review and update of the main fire risk model was conducted, leading to the introduction of dedicated branches in the main fire risk model event tree for *Detection*, *First response*, and *Decision*. The updated main fire risk model is described in section 9.4.1.

The main fire risk model and the associated sub-models were developed in such a way that it is possible to assess, in quantitative values, the consequences of additional preventing and mitigating measures addressing the risks of detection and decision failures.

Dedicated fault trees were developed focusing on the main hazards identified during the HazId. The trees were quantified to gain an understanding of the impacts on risks and to investigate in further detail the important causes and initiating events of the accident scenarios identified. This allowed quantification of the contributing detection failures as well as to calculate the overall detection failure rate. In order to consider the different types of ro-ro spaces, different trees were developed and quantified by investigation of available failure data, fire simulations, and expert judgement, in case none of the previous options were available. These trees are further detailed in the section 9.4.2.

Similarly, fault trees for decision failure were developed and quantified through dedicated human-element techniques and are described in section 9.4.4.

9.2 Early / Late detection discussion

9.2.1 *Objective and scope*

In fire safety, beyond the obvious objective of limiting the probability of having a fire, a key parameter is also to be able to detect the fire as soon as possible. The main reason for this is to allow for quick response in order to:

- Limit fire effects on people;
- Limit fire effects on structure and related systems;
- Limit effects on cargo;
- Limit fire effects on environment;
- Etc.

Although the previous statements are simple, it is not obvious how to clearly define what is meant by detecting a fire "*as soon as possible*". This implies that there would be a time/moment from which, even if the fire is detected, quick response would be limited or not possible.

Therefore, there is a need for defining a criterion to identify this time/moment, which is the objective of this task. Identification of "early" or "late" detection will allow developing a specific risk model for early/late detection and feeding into the coarse risk model for assessment of the fire risk.

9.2.2 *A criterion for "early" detection*

9.2.2.1 Expectations from an "early" detection criterion

Before defining an "early" detection, it is important to note the purpose of detection on-board ships.

According to SOLAS Chapter II-2, regulation 7.1 (covering detection): "*The purpose of this regulation is to detect a fire in the space of origin and to provide for alarm for safe escape and fire-fighting activity. […] fixed fire detection […] shall be suitable for the nature of the space, fire growth potential and potential generation of smoke and gases.*" Additionally, SOLAS II-2/20.4.1 specifies that "*the fixed fire detection system shall be capable of rapidly detecting the onset fire*". It is also stated in the deliverable D1.3 of the EU Funded R&D Project FIREPROOF (13/01/2011) (BMT, 2011) that "*its purpose* [i.e. purpose of a detection system] *is to detect a fire at its initial stage […].*"

Through this set of definitions/goals, hints can be identified for the definition of an "early" detection: detect the fire at its initial stage and provide for safe fire-fighting activity.

Detection can be influenced by many well-known factors, for example: the type and location of fire, the type of detectors, the ventilation conditions (mechanical or natural), the cargo arrangement, deck arrangement, etc. As far as practicable, the criterion for identifying an "early" detection should be able to take into account the possible influencing parameters.

Hence, the "early" detection criterion should:

- Reflect that a fire is detected at its early stage;
- Provide for safe fire-fighting activity; and
- Be applicable, no matter the fire scenarios considered (in other word, independent from the possible influencing factors).

It is also important to note that the definition of the "early" detection does not, in any way, prejudice the success or not of the fire extinguishment[14].

9.2.3 *Performance criteria for "early" detection*

A general agreement is made that the following timeline represents the usual best practices about fire safety events resulting from fire detection on-board a ship:

a. Fire starts;
b. Fire is detected:
- By a fire patrol/a crew member/a passenger ("human detection", including Manual Operated Call Point (MOCP));
- By the fixed fire detection system;

c. Visual and audible alarm (at the bridge notably):
    i. If the alarm is not acknowledged after 2 min, an audible fire alarm is to be automatically sounded throughout the crew accommodation and services spaces (then, set up of the "Decision" chain, cf. below);

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[14] If the detection of a fire can be considered as « early », many other parameters not related to the detection can influence the capability of extinguishing that fire (availability of the fixed-fire extinguishing system, decisions made by the crew, etc.).

ii. If alarm is acknowledged, set up is made of a “Decision” chain which may result in different actions (manual fire attack, activation of automatic fire suppressions systems, intervention of firefighters, etc.)[15].

For the purpose of this section, as a conservative approach, it is assumed that the first response will be initiated. However, some may disregard this step and instead trust their technical aids for confirmation of fire and subsequently activate the fixed system based on this information (e.g. when it is known that the personnel will not reach the location in time for first response, hence the priority is to have the fixed system activated and get a fire fighting team in there as soon as possible).

Bearing in mind this general time-line, it is considered that an ideal situation (bringing the idea that the detection is sufficiently early) would be that the whole chain of events would enable crew members to attack the fire safely by manual means.

A safe first response is typically only possible during the early stages of a fire, during which fire effluents are such that they do not compromise the life safety of people setting up the first response, hence the importance of early detection.

Henceforth, the question is how to assess effects of fire effluents with respect to life safety. The MSC circular MSC/Circ. 1002 on “*Guidelines on Alternative Design and Arrangements for Fire Safety*” (IMO, 2001), as amended by MSC.1/Circ. 1552 (IMO, 2016), provides life safety performance criteria to be used when evaluating the elapsed time before the effects of fire and smoke directly impact occupant tenability. These are:

- Maximum air temperature:	60°C;
- Maximum radiant heat flux:	2.5 kW/m²;
- Minimum visibility:	10 m (or 5m in spaces ≤ 100 m²); and
- Maximum CO concentration:	1200 ppm (instantaneous exposure) or 500 ppm (for 20 min cumulative exposure times).

In our case the above-mentioned occupant would be a responder, who can be either a crew member or a passenger. These quantities will be taken into consideration to assess the atmosphere in the vicinity of the fire, i.e. at a distance called $\boldsymbol{D_{eff}}$ from the fire. $\boldsymbol{D_{eff}}$ is discussed later (cf. paragraph 9.2.4.2).

This allows determining the *Available Time for Safe First Response* (ATSFR), which is – from the time of ignition to the thresholds being exceeded at 1.8 m above the deck in question and a distance D_{eff} from the fire – the time frame required to maintain tenability. The value 1.8 m refers to a conservative average top height of an uncovered head.

The **ATSFR** is compared to the *Required Time for Safe First Response* (**RTSFR**), which is the time to detect the fire (by automatic or manual means) as well as the time necessary to set up all the appropriate first response actions following detection. In other words:

$$\mathbf{RTSFR} = \mathbf{t_d} + \mathbf{T}$$

Where:

- $\mathbf{t_d}$ is the detection time of the fire (by automatic or manual means); and
- **T** is a constant that takes into account the different actions following the detection for safe first response (time for the first responder(s) to go on site, time for manual first response decision, etc.). **T** should be explicitly provided and documented according to the on-board procedures of the owner.

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[15] Non-exhaustive list and not chronological sequence

9.2.4 *Test case, selection of D_{eff} and “early” detection criterion*

9.2.4.1 Test case

In order to test the relevance of the proposed performance criteria (especially the **ATSFR**) and to define the distance D_{eff}, a simple test case was modelled and simulated using the Code FDS (Fire Dynamics Simulator), further presented in paragraph 9.3.1.1.3.

9.2.4.1.1 Model data

The Table 12 presents the basic model data.

Table 12: Model data

Mesh dimensions (L x l x H)	7 m x 3 m x 3 m
Cell size	10 cm
Boundary conditions	Open
Surface on fire	1 m²
Growing phase[16]	Medium
Simulated time	600 s
Ceiling and floor material	Steel
Sensor’s spacing (in front of the fire)	1 m (from 1 m to 4 m)
Soot yield	0.12 g/g
CO yield	0.036 g/g

The burning material considered is rigid polyurethane. Soot and CO yields are extracted from the SFPE Handbook (National Fire Protection Association, 2002). The material and values used in the simulation are very conservative and adequate for a near field evaluation.

The fire seat is located 1.2 m above deck height (approximately a car hood height).

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[16] According to FIRESAFE, in fire safety engineering, the fire growth is often simplified and described as a so called “T-squared” fire, i.e. the heat release rate (HRR) increases proportionally to the square of time. Based on experiences from car fires (FIRESAFE), a medium fire growth is considered to be the expected fire growth for ro-ro space fires. In most cases, this can be considered conservative.

Figure 20 presents a view of the model. Green dots are the sensors where the quantities listed in paragraph 9.2.3 are measured. They are placed 1.8 m above deck height.

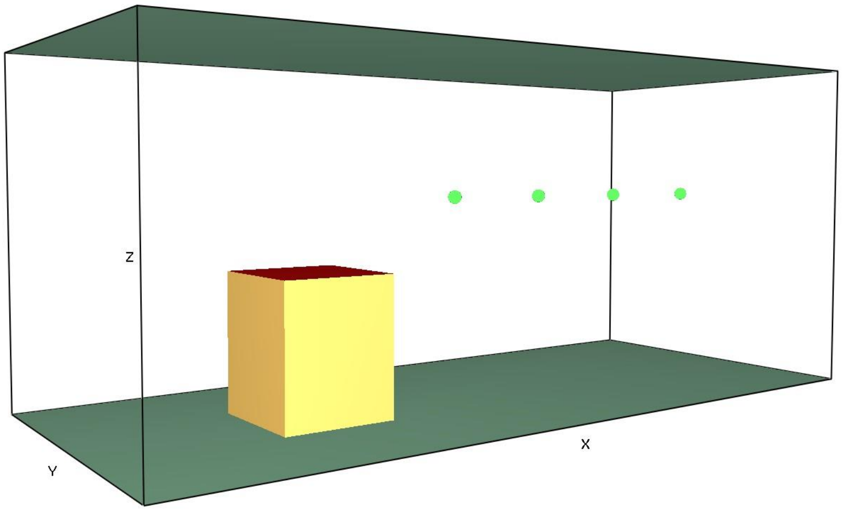

Figure 20: View of the model in SmokeView

9.2.4.1.2 Results

Within the simulated time, it is to note that only the radiant heat flux exceeds its threshold value (TV) of 2.5 kW/m². Although this result was expected due to the open boundary conditions of the model itself, it is presumed that in most situations, the radiant heat flux will, if one considers the available volume for the smoke to spread in open ro-ro spaces, remain the governing parameter in the vicinity of the fire. Nonetheless, all quantities should be evaluated (cf. paragraph 9.2.3).

Figure 21 presents the time when the radiant heat flux TV is exceeded, at different distances from the fire, and the corresponding HRR (for information purpose only).

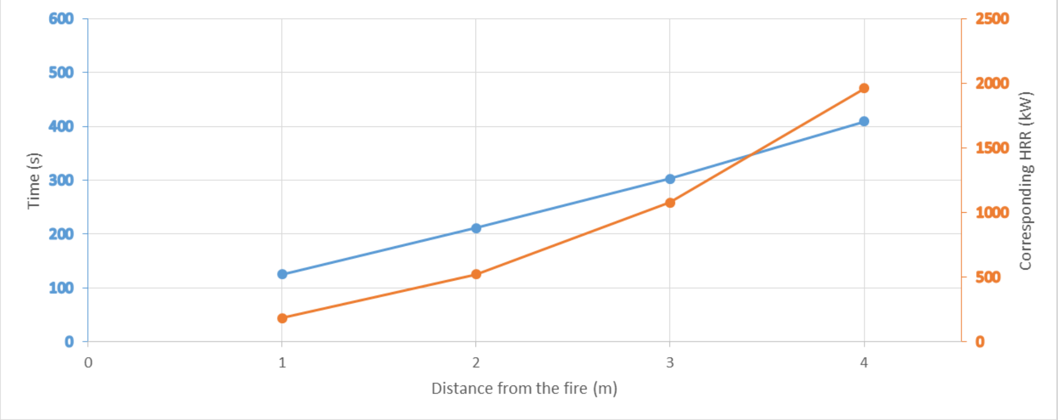

Figure 21: Radiant heat flux - Time TV exceeded & corresponding HRR

The radiant heat flux decreases with the distance ***D*eff**. Indeed, the TV of 2.5 kW/m² is exceeded at around t = 120 s at a distance of 1 m from the fire, while it is exceeded at around t = 410 s at a distance of 4 m from the fire.

9.2.4.2 Selection of D_{eff}

As already discussed in paragraph 9.2.2.1, the “early” detection criterion should be based on the capacity to attempt a first response on the fire in safe conditions. It is commonly agreed that on a ro-ro space, the first response consists of the use of portable fire extinguishers.

According to SOLAS Convention (Chap. II-2/20.6.2.1), "*Portable fire extinguishers shall be provided at each deck level in each hold or compartment where vehicles are carried, spaced not more than 20 m apart on both sides of the space. At least one portable fire extinguisher shall be located at each access to such a cargo space.*"

Although there are no clear recommendations with regard to the type of fire extinguisher that should be available on ro-ro spaces, it does nonetheless seem like powder portable fire extinguishers are the preferred choice among ship operators. This is likely due to their effectiveness against the specific types of fires most likely to occur on ro-ro spaces, e.g. electrical fires. The general effective range of such portable fire extinguishers is between 3 m and 5 m (Bureau Assistance Technique Prevention Incendie, s.d.).

Considering the previous statements and the results presented in Figure 21, the distance from the fire where quantities should be evaluated for the "early" detection criterion is D_{eff} = 4 m.

9.2.4.3 "Early" detection criterion

The proposed criterion for early detection is **RTSFR ≤ ATSFR** at the distance D_{eff} = 4 m from the fire.

This is in line with the expectancies described in paragraph 9.2.2.1.

9.2.5 Discussions

9.2.5.1 Limitations of analytical solutions

The results presented in the previous paragraphs could have been derived, to a certain extent, using literature and analytical solutions of radiation calculations. More specifically, similar results could presumably have been achieved either by a) assuming a point source for the agent exposed to the radiation while also assuming that the flame behaves as a vertical rectangle and then performing the relevant hand calculations, or b) calculations from the correlation proposed by Shokri and Beyler (Drysdale, 2011). However, these methods do not apply at short distances from the fire (without any specification on what "short distances" means in practical terms) and moreover assume that the flames are vertical. Considering the fire development presented in paragraph 9.2.4.1.1, it is observed that the flame height rapidly exceeds 2 m, giving the flame a bent shape due to ceiling impingement. This effect is taken into account in the numerical simulations but not in the analytical solutions just mentioned.

9.2.5.2 Fractional effective dose of heat

Another advantage using the CFD computations in the presented test case is that they allowed calculating the fractional effective dose of heat (FED_{Heat}). FED_{Heat} represents the dose of heat received by an agent (crew member, pax, etc.) during an exposure time. It considers the effects of radiant heat and exposure to convective heat from hot gases. As a conservative assumption and considering the test case, the exposure time was defined as the time frame beginning at t = 0 s to the time when the radiant heat flux TV is exceeded at the distance D_{eff} from the fire, plus an additional time of 16 s corresponding to the time needed to empty a classical 6 L powder portable fire extinguisher. Finally, FED_{Heat} is about 0.18, which is below the limit of 0.3 (MSC.1/Circ. 1552). This result strengthens the relevance of the criterion.

9.2.5.3 Parameters influencing the radiant heat flux

The radiant heat flux received from a flame depends on a number of factors. As a non-exhaustive list, the following ones can be named: the flame temperature, the flame thickness, the concentration of the soot and other combustion products, the geometric relationship between the flame and the "receiver", i.e. the view factor, etc. All these are connected to the fire scenario considered. The general nature of the proposed criterion for the "early" detection allows it to be adapted to various fire scenarios and to take into account these possible influencing parameters.

9.2.5.4 Wind effect and mechanical ventilation

In case of open ro-ro space or weather deck, the wind can have an influence on the flame. Indeed, the flame will be deflected by air movement, the extent of which will depend on the wind velocity and the heat release rate of the fire. Depending on the wind direction, one will have to be careful when evaluating the “early” detection criterion. The common sense would then be to attempt the first response windward. Therefore, the criterion should be evaluated accordingly.

The same conclusion applies to mechanical ventilation in closed ro-ro spaces, where strong air flows could be observed.

9.3 Early / Late detection simulations

9.3.1 *Scenario definition for simulations: “early/late” detection*

In the context of FIRESAFE II, one of the objectives of defining an “early/late” criterion for detection is to feed the fault tree for detection contributing to the assessment of the overall fire risk and later assess the impact of the selected RCOs.

Based on the risk model developed and the nature of the “early/late” detection criterion, only few branches can be further investigated through numerical simulations (these branches are described in paragraph 9.4.2.1). For example, fire simulations are not able to represent the effect of having higher frequencies of fire patrol on a cargo deck.

They focused on the main parameters of a fire scenario that could have an influence on the detection, for example: fire growth, soot yield, type of detectors, etc.

9.3.1.1 Fire scenario parameters influencing detection and definition of fire scenarios

The aim of this paragraph is firstly to list all the main parameters related to the definition of a fire scenario that could have an impact on the fire detection. Secondly, based on expert judgements, a limited number of relevant configurations for each parameter were established in order to have a reduced number of fire scenarios to simulate.

9.3.1.1.1 Fire scenario parameters influencing detection

9.3.1.1.1.1 Fixed fire detection

Nowadays, the general performance requirements on fixed fire detection system are listed in SOLAS II-2/20.4.1, where it is stated that:

- “The fixed fire detection system shall be capable of rapidly detecting the onset of fire”
- “After being installed, the system shall be tested under normal ventilation conditions and shall give an overall response time to the satisfaction of the Administration”

Common practice as per BV field experience is to perform this test using a smoke generator. A usual criterion is that the fire detection system is to be activated within 3 minutes.

Even though the type of detectors is not clearly specified, common practice is to use smoke detectors.

Therefore, the investigated parameters of fire scenarios that could influence detection concern those influencing smoke, i.e. smoke propagation and smoke production.

9.3.1.1.1.2 Main fire scenario parameters influencing smoke detection

8 parameters were identified as relevant to be investigated. They are:

- The type of deck;
- The deck loading configuration;
- The fire location;
- The fire growth;
- The soot yield;
- The ship’s speed;
- The wind’s speed; and
- The wind direction.

Table 13 summarises the parameters influencing smoke detection and their related possible challenging configurations.

Table 13: Main fire scenario parameters influencing smoke detection (Open ro-ro space)

Parameter	**Number of configurations**	**Comments**
Type of deck	3	3 types of cargo deck are studied: open ro-ro space, closed ro-ro space and weather deck
Deck loading configuration	2	Fully loaded and partially loaded
Fire location	6	Assuming a symmetrical loading configuration (related to the ship's longitudinal axis): 2 fire locations fore of the deck, 2 at the middle of the deck and 2 aft of the deck
Fire growth	3	Based on FIRESAFE report: slow / medium / fast fire growing phases
Soot yield	2	Low / High
Ship's speed	2	At port (v=0 knot) / At sea (nominal ship's speed)
Wind's speed	2	No wind / Windy condition (cf. discussion on paragraph 9.3.1.1.2.7)
Wind direction	4	Apparent wind. Headwind, tailwind and 2 crosswinds (i.e. wind blow the smoke inside the deck or outside the deck)

In the context of the study, the type of ventilation conditions (i.e. mechanical or natural) is directly related to the type of deck considered. As a consequence, they are not listed in Table 13, as they are inherent parameters of the deck type studied.

9.3.1.1.2 Fire scenarios definition

Considering together the 8 parameters listed above would lead to a total number of fire scenarios equal to 2 160. The modelling and the simulations of all of them would take far too much time and be too CPU consuming (for information purpose, the time to simulate 600s of fire with wind conditions is about 13 days). It is, for purely practical reasons, therefore necessary to reduce the total number of scenarios to be further investigated.

9.3.1.1.2.1 Deck types

FIRESAFE II focuses on the three types of ro-ro spaces: the open ro-ro space, the closed ro-ro space and the weather deck. By definition, the weather deck is completely exposed to the weather from the above and from at least two sides. No detection is required as per SOLAS. Weather decks will thus not be further considered at this stage of the study.

9.3.1.1.2.2 Deck loading configurations

The number of deck loading configurations is reduced to only 1, i.e. a fully loaded car deck.

9.3.1.1.2.3 Fire locations

The initial number of fire locations to consider is 6. Among these, 3 were identified as more challenging with regard to detection. They are presented in Figure 22 in blue (those eliminated are marked with a red cross).

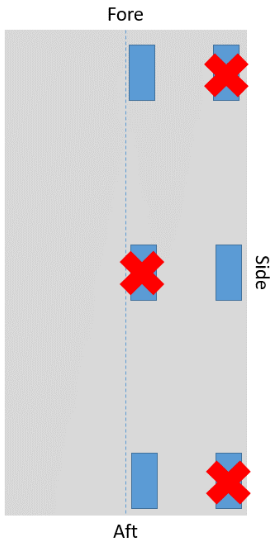

Figure 22: Selected fire locations

9.3.1.1.2.4 Fire growth

According to FIRESAFE report: "*[…] a medium fire growth is considered to be the expected fire growth rate for ro-ro deck fire, in most car fire scenarios this can be considered conservative.*" Based on this statement and considering that a fast fire growth phase would probably lead to late detection, it is decided to focus mainly on slow and medium fire growing phases.

9.3.1.1.2.5 Soot yield and average burning molecule

In a first approach, it was decided to focus on only one soot yield. The fire load of passenger cars is around 5-8GJ/car (Li, 2004). To get this value and maintain some characteristics of polymers (e.g. polystyrene, Polyurethane) in terms of chemical formula, the average burning molecule considered in the simulations is $C_{6.3}\ H_{7.1}\ O_{0.8}$. The soot yield and CO yield for passenger cars are considered to be 0.06 g/g and 0.1 g/g respectively.

9.3.1.1.2.6 Ship's speed

When the ship is at port, her speed is v = 0 knot. According to FIRESAFE II consortium, it means that the ship is probably under loading / unloading conditions. In other words, there is a high probability of having the smoke detection system deactivated. Additionally, the presence of many crew members during these operations would probably lead to human detection instead of automatic fire detection. Consequently, v = 0 knot is not further investigated.

9.3.1.1.2.7 Wind's speed and directions

It should be noted that the simulated case represents the ship at sea. Therefore, due to the ship's speed, one obvious situation is when the ship is sailing and consequently creates its own apparent wind. The apparent headwind situation is then retained.

Other challenging situations include wind blowing from the sides of the ship creating two situations: either the fire is located windward, consequently blowing the smoke inside the car deck; or the fire is located leeward and thereupon blowing the smoke out of the car deck. These two situations are considered to be relevant and challenging regarding the purpose of the study.

Concerning the wind coming from aft of the ship, except in rare situations (at port or in extremely bad weather), the chances of having this apparent wind are very low. Apparent tailwind is then not considered.

The speed of the apparent headwind is considered to be 20 knots, while the apparent crosswind speeds are supposed to be equal to 10 knots.

9.3.1.1.3 Fire Dynamics Simulator (FDS)

The software used for the numerical simulations is Fire Dynamics Simulator (FDS). FDS is a computational fluid dynamics (CFD) model of fire-driven flow. FDS solves a form of the Navier-Stokes equations appropriate for low-speed (Ma < 0.3), thermally-driven flow with an emphasis on smoke and heat transport from fire.

9.3.2 *Modelling assumptions*

9.3.2.1 References

In order to model the geometry of the open ro-ro space (of the *Standard RoPax*) and the different fire scenarios the following documents from the *Standard RoPax*, provided to Stena, were used:

- General Arrangement
- Fire Control Plan
- Open ro-ro space GA
- Open ro-ro space GA incl. fire zones
- Open ro-ro space Concept
- Mid Ship Section
- Venting System Outside E.R
- Fire detection system technical specifications

In order to run the closed ro-ro spaces scenarios, the deck 3 / 4 of the *Ferry RoPax* was modelled. The same kind of reference documents from the *Ferry RoPax* were used.

9.3.2.2 Geometry modelling

In the fire models, some spaces have not been modelled in detail because they do not significantly participate in the fire development. These are:

- The stairways;
- The lifts;
- The stores;
- The funnel; and
- All other technical spaces that are not inside the car deck.

These spaces were modelled by solid obstructions.

Cars and trucks were placed randomly on the car deck. They are respectively represented by yellow blocks and blue blocks.

The A class division bulkheads are in accordance with the documents provided by Stena. Typical configuration and materials of A class divisions are standard for maritime applications (mineral wool insulated steel according to SOLAS standards).

In the fire scenarios, the fire is considered to develop at a prescribed rate (see section 9.3.2.6) and is not controlled by any other mean (this is a conservative approach).

9.3.2.3 Geometry modelling – Open ro-ro space

The geometry modelling of the deck 4 (open ro-ro space of the *Standard RoPax*) is based on the documents cited above.

Figure 23 presents the general arrangement of Deck 4.

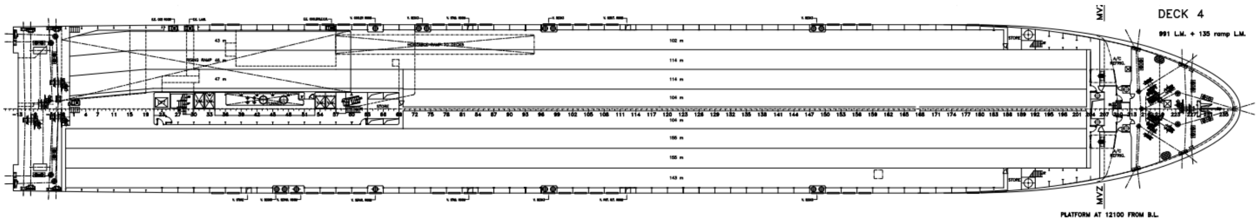

Figure 23: ***Standard RoPax*** **- Deck 4**

Figure 24 and Figure 25 present some views of the model. Sensors were placed in the model as measurement points for ATSFR criteria, as well as smoke detectors.

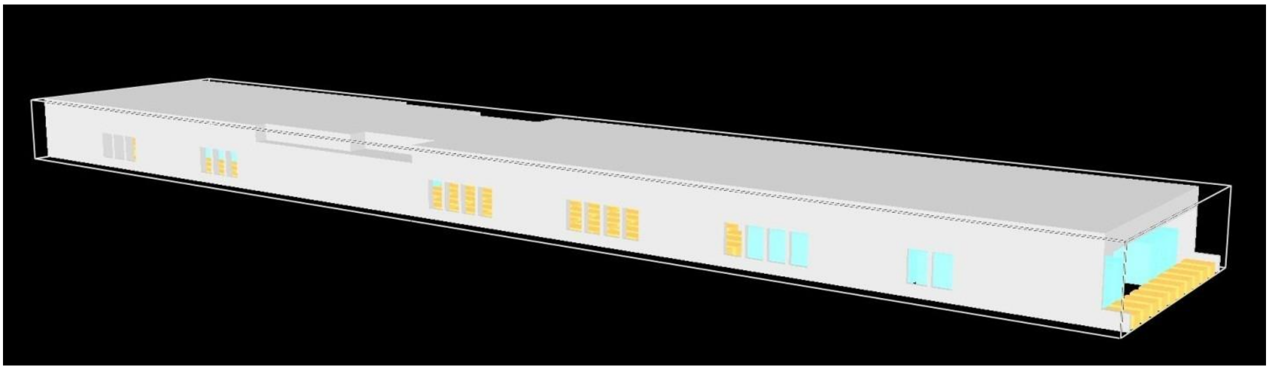

Figure 24: Deck 4 - Side view (port side)

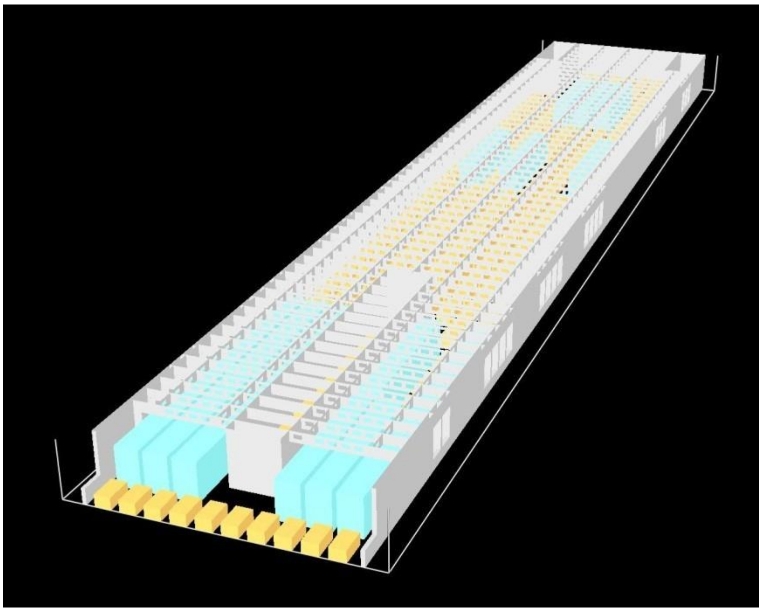

Figure 25: Deck 4 - Aft view (with clip upper)

9.3.2.4 Geometry modelling – Closed ro-ro space

The geometry modelling of the deck 3 / 4 (closed ro-ro space of the Ferry RoPax) is based on the documents referenced in paragraph 9.3.2.1.

Figure 26 presents the general arrangement of Deck 3 / 4.

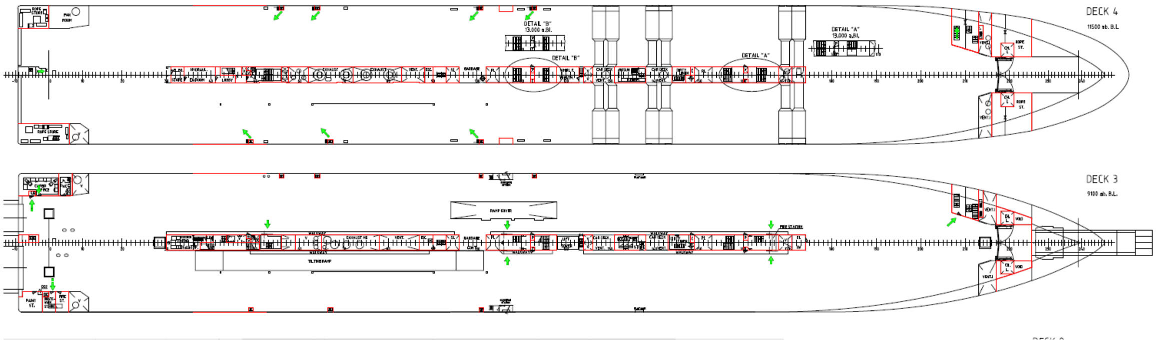

Figure 26: ***Ferry RoPax*** **- Deck 3/4**

Figure 27 and Figure 28 present some views of the model. Sensors were placed in the model as measurement points for ATSFR criteria, as well as smoke detectors.

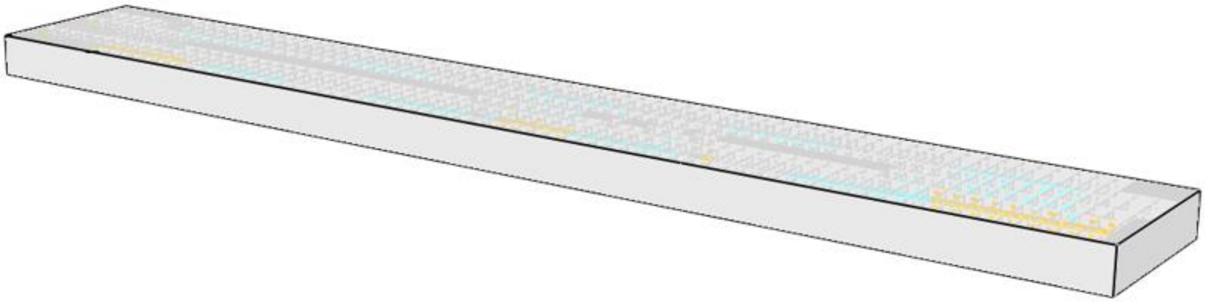

Figure 27: Deck 3/4 - Side view

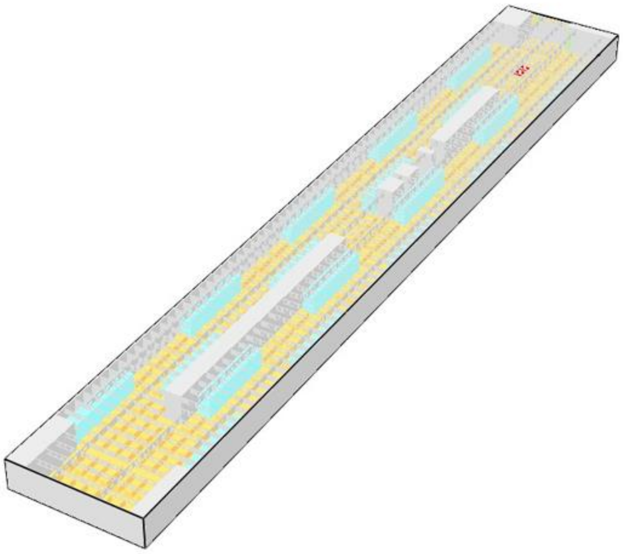

Figure 28: Deck 3/4 - Aft view

9.3.2.5 CFD mesh

In both cases and for all fire scenarios, a multi-mesh modelling was carried out.

In the zone of flaming, a mesh of 20 cm x 20 cm x 20 cm is considered, whereas other meshes have cells of 40 cm x 40 cm x 40 cm.

9.3.2.6 Heat release rate

The fire starts at t = 0s and has either a slow growing phase (600 s to reach 1 MW, cf. Figure 29) or a medium growing phase (300 s to reach 1 MW, cf. Figure 29).

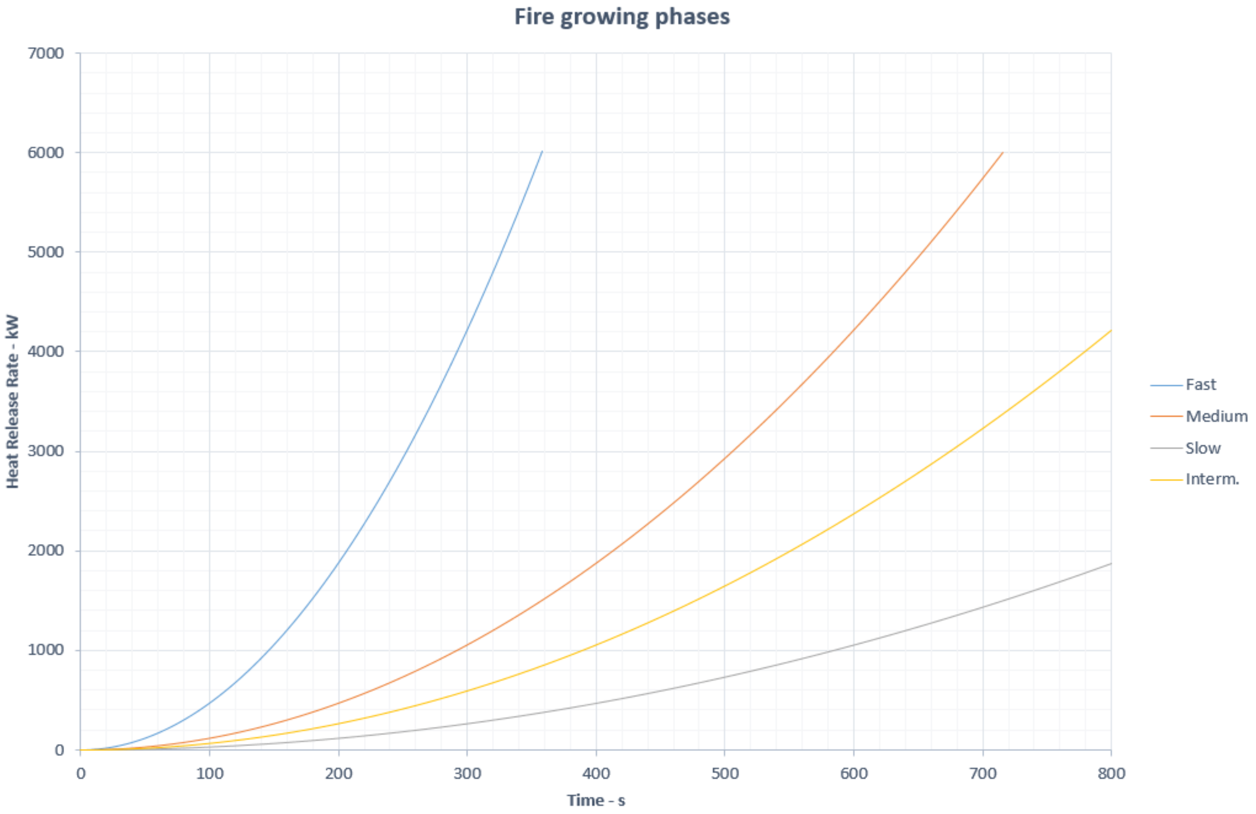

Figure 29: Fire curve – Slow, Interm., Medium, and Fast growing phases

The fire keeps developing long enough for the evaluation of the “early/late” detection criterion. In practical terms, the simulations are launched for a fixed duration time e.g. 1000s. They can be interrupted when one of the Threshold Value is passed as there is already enough information to evaluate the early/late criterion.

9.3.2.7 Ventilation – Open ro-ro space

The open ro-ro space is naturally ventilated (i.e. no mechanical ventilation system). The locations and the sizes of the opening[17] were implemented according to the documents referenced in paragraph 9.3.2.1.

9.3.2.8 Ventilation – Closed ro-ro space

The present closed space was assumed to have no side openings to the outside but mechanical ventilation was provided with 10 air changes per hour (acph). This rate corresponds to a speed of air at the outlet of the ventilation fan of 2.41 m/s. Positions and area of fan outlets were extracted from the documents referenced in paragraph 9.3.2.1.

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[17] Openings size (per opening): 3x2 m (h x b), except for the openings forward of the LSAs, which are slightly lower: 2.8 m.

9.3.3 *Results – Open ro-ro spaces*

As a reminder, the objective of this set of simulations is to identify whether detection of the fire happens early enough (i.e. according to the defined criterion) to allow for safe first response.

In the open ro-ro space case, a total number of 18 design fire scenarios without RCOs and 6 design fire scenarios with RCOs were further investigated. In addition to those scenarios, during the study, 9 other scenarios corresponding to a new fire curve (intermediate growing phase (T-squared), i.e. between slow and medium growing phase fires) were considered and are presented as "Interm."

Table 14 summarises the results in terms of detection time.

Table 14: Simulation results for the open-deck configuration. ND = No Detection within the simulated time, HF = Heat Flux, V = Visibility

Scenario				First smoke detection - s	Second smoke detection - s	ATSFR - s	Quantity
No Wind	*Slow*	*L1*		80.0	81.0	797.0	HF
		L2		81.0	149.0	973.0	HF
		L3		106.0	118.0	812.0	HF
	Interm.	*L1*		59.0	68.0	532.0	HF
		L2		61.0	107.0	678.0	HF
		L3		81.0	86.0	564.0	HF
	Medium	*L1*		52.0	53.0	415.0	HF
		L2		54.0	103.0	518.0	HF
		L3		66.0	75.0	424.0	HF
			Wind origin				
Wind	*Slow*	*L2*	*Fore*	339.0	438.0	1134.0	HF
			Port	ND	ND	-	-
			Starboard	618.0	ND	964.0	HF
	Interm.	*L2*	*Fore*	274.0	292.0	739.0	HF
			Port	ND	ND	897.0	HF
			Starboard	339.0	388.0	913.0	HF
	Medium	*L1*	*Fore*	89.0	96.0	350.0	V
			Port	84.0	126.0	367.0	V
			Starboard	83.0	111.0	362.0	V
		L2	*Fore*	244.0	246.0	561.0	HF
			Port	ND	ND	672.0	HF
			Starboard	311.0	385.0	690.0	HF
		L3	*Fore*	222.0	377.0	371.0	HF
			Port	98.0	132.0	492.0	HF
			Starboard	118.0	232.0	482.0	HF

9.3.3.1 Detection time analysis

First, the different simulation results are compared in terms of time of detection. The threshold value for the smoke detection is an obscuration of 3.28% / m, which is a common sensitivity of smoke detectors.

9.3.3.1.1 No wind

Without wind, the smoke detectors detect the fire around 55-105 s for the first activated detector and then up to 150s for the second activated detector. Also, the hierarchy of the fire growing phases for the first detection is respected: the medium growing phase is detected before the intermediate growing phase (about 10s on average), itself detected before the slow growing phase (about 12s on average).

9.3.3.1.2 Wind

9.3.3.1.2.1 Slow growing phase fire

The main observation in these scenarios is that the smoke detectors do not detect the fire in some cases. For example, when the wind is blowing the smoke and heat out of the ship through the openings, there is no detection (wind coming from Port side, cf. Figure 30). This is a critical scenario. However, it should be noted that with another cargo configuration, possibly with trucks or trailers in front of the opening, the results could have been different.

The other wind conditions result in detection in 339 s and 618 s for the wind blowing from the directions fore and starboard respectively. The second detection is also activated, but only with the wind blowing from fore of the ship. Compared to the case without wind, this is around 4-6 times longer. This is due to the smoke being diluted by the wind.

9.3.3.1.2.2 Intermediate growing phase fire

The same remarks as in the previous paragraph apply in the intermediate growing phase fire scenarios with wind, i.e. the smoke detectors do not detect the fire in some cases (wind coming from port side, blowing the smoke and heat out of the ship through the openings). Another cargo configuration could have led to different results.

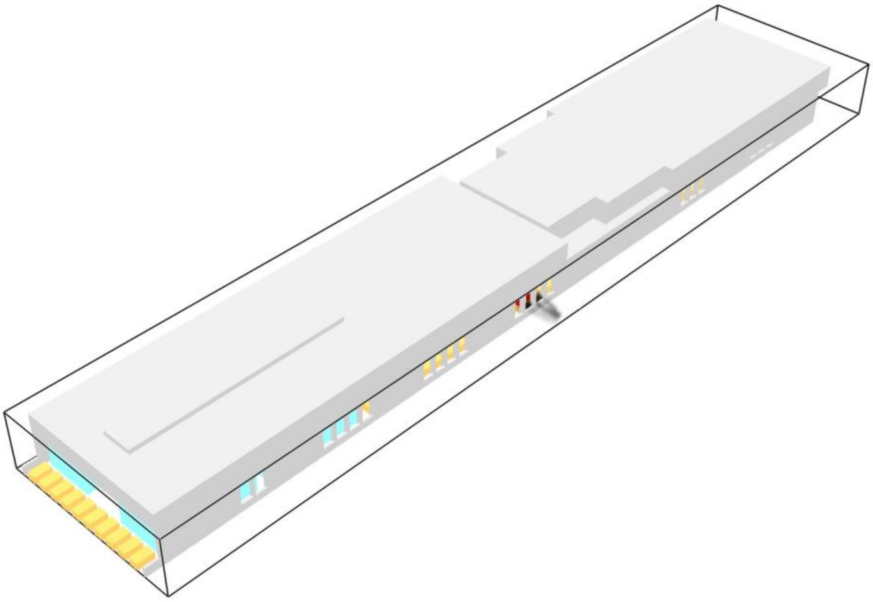

Figure 30: Wind coming from port side - Smoke spreading outside the deck - t = 300 s

The other wind conditions result in detection in 274 s and 339 s for the wind blowing from the directions fore and starboard respectively. The second detection is also activated. Compared to the case without wind, this is around 4-6 times longer. This is due to the smoke being diluted by the wind.

9.3.3.1.2.3 Medium fire

In the case of a medium fire growth with the wind coming from port side, the location L2 for the fire seat still results in no detection (smoke). This is also a critical scenario.

The other scenarios are all detected by the smoke detector. The ones detected the earlier are the scenarios for the location of the fire seat L1, followed by the L3 and finally L2.

Meanwhile the results for L1 are not very influenced by the wind direction (around 80 s), the location L2 and L3 display a strong dependence on the wind direction with detection time ranging from 244 s to no detection for L2 and from 98 s to 222 s for L3.

9.3.3.2 ATSFR analysis

As mentioned in the section 9.2.5.4, the wind, through deflection of flames and smoke, produces a non-homogenous contour of heat radiation and smokes around the fire seat. This results in different time to exceed the criteria depending on the relative position to the fires seat and the wind direction. In particular, the sensors located downwind exceed the ATFSR criterion earlier than in the windward direction. These points are not considered in the following analysis because it seems natural that in the event of a first response, the common sense would be to place oneself windward - if possible in regard to physical restraints.

In the absence of wind, the ATSFR is exceeded only regarding the heat flux threshold. The time of exceedance appears to be influenced by the fire growth rate. The scenarios corresponding to an intermediate fire exceed the criterion about 150 s later than the medium fires, i.e. respectively around 550-650 s and 400-500 s. The trend increases when comparing the slow fire to the intermediate one.

A special attention should be paid on the case considering wind coming from port side of the ship and a fire with a slow growing phase. In that particular case, the ATSFR is not given as during the simulated time, no quantity (visibility, heat flux, etc.) exceeds its threshold value. As no detection was observed, no conclusion can be made.

The general trend, both in wind cases and no wind cases, it that the slower is the growing phase of the fire, the longest is the ATSFR.

It can also be observed that in the wind cases, the ATSFR are longer than in the no wind cases (when comparing equivalent scenarios). These overall larger times are thought to be the consequence of having a consequent part of the heat and smoke leaving the ship through the openings. It should be noted that considering a fixed detection time, this effect could change a late scenario to an early one.

When considering the effect of wind, the ATSFR was exceeded regarding the heat flux threshold as well as in some cases the visibility criteria. The later was observed in the configuration where the fire seats are fore of the ship, for a medium fire growth and for all the considered wind directions. This is explained by the higher degree of confinement in this location (see the trucks in blue in the Figure 31). The consequence is an earlier exceedance of the criteria (around 350 s against 415 s without wind).

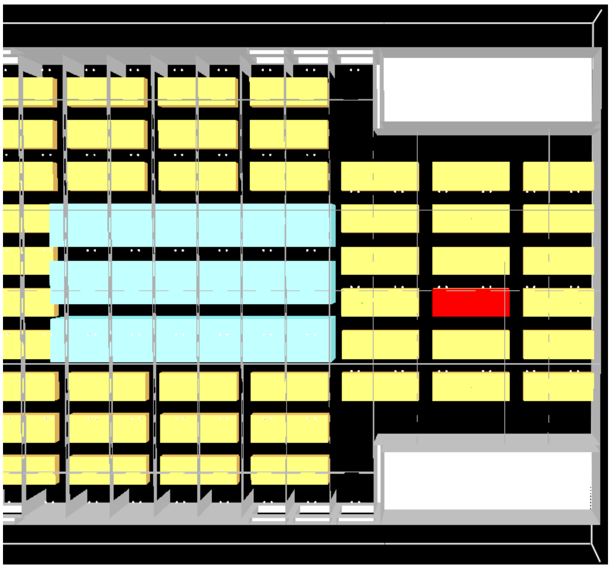

Figure 31: Fire seat L1 (red) - Top view

Besides, when the fire seats at the aft of the ship (L3), the visibility criteria was not exceeded before the heat flux. However, the values remained very close to exceedance whatever the wind direction.

9.3.3.3 *Early/late analysis*

In the Table 15, the same results are presented in terms of early versus late detection using the concept presented in 9.2.4.3. Sensitivity to the *T* constant was studied using values ranging from 2 to 5 minutes. Positive results are obtained when the detection is considered early, the value indicates the margin. When the result is negative, the detection is considered late, the value indicating the delay.

Table 15: Simulation results for the open-deck configuration in term of early vs. late detection. Early detection is presented in green, late detection in orange

Scenario				Criteria for early detection - 0 ≤ (ATSFR-RTSFR (2min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (3min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (4min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (5min)) - s
No Wind	*Slow*	*L1*		597.0	537.0	477.0	417.0
		L2		772.0	712.0	652.0	592.0
		L3		586.0	526.0	466.0	406.0
	Interm.	*L1*		353.0	293.0	233.0	173.0
		L2		497.0	437.0	377.0	317.0
		L3		363.0	303.0	243.0	183.0
	Medium	*L1*		243.0	183.0	123.0	63.0
		L2		344.0	284.0	224.0	164.0
		L3		238.0	178.0	118.0	58.0
			Wind origin				
Wind	*Slow*	*L2*	*Fore*	675.0	615.0	555.0	495.0
			Port	-	-	-	-
			Starboard	226.0	166.0	106.0	46.0
	Interm.	*L2*	*Fore*	345.0	285.0	225.0	165.0
			Port	-897.0	-897.0	-897.0	-897.0
			Starboard	454.0	394.0	334.0	274.0
	Medium	*L1*	*Fore*	141.0	81.0	21.0	-39.0
			Port	163.0	103.0	43.0	-17.0
			Starboard	159.0	99.0	39.0	-21.0
		L2	*Fore*	197.0	137.0	77.0	17.0
			Port	-672.0	-672.0	-672.0	-672.0
			Starboard	259.0	199.0	139.0	79.0
		L3	*Fore*	29.0	-31.0	-91.0	-151.0
			Port	274.0	214.0	154.0	94.0
			Starboard	244.0	184.0	124.0	64.0

9.3.3.3.1 No wind

There is an overall good performance of the detection in the cases without wind. Indeed, according to the definition of early/late based on the ATSFR criterion and assessing a constant between 2 and 5 minutes, all the simulations resulted in early detections. This is achieved thank to a low detection time and at the same time a relatively long time required to exceed the thresholds defined for the ATSFR. However, as the fire growth increases, the margins decrease. Therefore, it can be anticipated that fast growing phase fires would even more reduce the difference between first detection and ATSFR, leading to criteria closer to late detection than early detection. Consequently, they were not simulated.

9.3.3.3.2 Wind

9.3.3.3.2.1 Slow

When the fire is located in L2, as exposed previously, no detection occurs and no quantity exceeds its threshold value within the simulated time. Therefore, no obvious conclusion can be made on that particular case which appears to be anyway a critical case.

The other scenarios lead to early detection. Indeed, the fire is detected quite quickly and, in the meantime, the fire is not powerful enough to produce large amount of smoke and heat that could be dangerous for life safety.

9.3.3.3.2.2 Intermediate

When the fire is located in L2, the only scenario leading to a late detection is the one with the wind blowing the smoke and heat out to the ship through the opening. The fire was not even detected after around 800 s of simulation.

Concerning the two other scenarios, even considering a 5 minutes response time, the detection is still early. This is also a consequence of the longer time required to pass the criterion from 678 s without wind to 739-913 s depending on the wind direction. When the wind blows toward the starboard side, the fire is detected a bit later (around 60 s) than in the case where the wind is blowing from the fore of the ship but still early enough to give an early detection.

9.3.3.3.2.3 Medium

Considering the location L1, there is an overall good performance of the detection which results in an early detection as long as the time required for the first response is lower than 5 minutes.

Location L3 exhibits also early detection for every case, with the exception of the one with wind coming from the fore of the ship, when the reaction time is above 2 minutes, it becomes late detection.

Finally for the location L2, early detection is obtained except when the wind is coming from the portside where the detection is not activated.

9.3.4 *Closed ro-ro space scenarios*

9.3.4.1 Results

The objective of this set of simulations is to identify in the defined fire scenarios for the closed ro-ro space, if the detection of the fire happens early enough (i.e. according to the defined criterion) to allow for safe first response.

Table 16 summarises the results in terms of detection time.

Table 16: Simulation results for the closed ro-ro space configuration. ND = No Detection within the simulated time, HF = Heat Flux, V = Visibility

Scenarios			Time of detection (smoke) - s (3.28%/m)	Second smoke detection - s	ATSFR -s	Quantity
Fire Growth	Position of fire	Ventilation				
Slow	L3	Normal	82	119	-	-
Slow	L2	Normal	94	122	-	-
Slow	L1	Normal	80	99	-	-
Medium	L3	Normal	72	90	395	HF
Medium	L2	Normal	61	61	413	HF
Medium	L1	Normal	66	72	428	HF
Fast	L3	Normal	41	59	197	HF
Fast	L2	Normal	37	46	209	HF
Fast	L1	Normal	54	68	216	HF
Fast	L2	Half	48	51	206	HF
Medium	L2	Half	60	68	413	HF
Fast	L2	Double	36	45	210	HF
Medium	L2	Double	62	78	445	HF

9.3.4.2 Detection time analysis

As for the open ro-ro space simulations, the different simulation results are compared in terms of time of detection. The threshold value for the smoke detection is an obscuration of 3.28% / m, which is a common sensitivity of smoke detectors.

9.3.4.2.1 Positions of the fire

The main result of simulations here is that the influence of the position of the fire on the time of smoke detection seems random. Indeed, no general law can be find out. The time of detection seems more influenced by the fire growth than the fire position.

9.3.4.2.1.1 Fire growth

As expected, the time of smoke detection is lower for fast fire growth than medium fire growth, and lower for medium than slow fire growth.

9.3.4.2.1.2 Ventilation

The influence of ventilation on the time of smoke detection seems counterintuitive for the case of fast fire growth. Indeed, the results show that the time of smoke detection is similar when the ventilation is double and higher when the ventilation is half. For the case of medium fire growth, the time of detection is similar for all three cases. This result shows that it is difficult to find rules about smoke detection. The smoke detection is based on smoke production, position of the fire related to detector and influence of wind /ventilation)

9.3.4.3 ATSFR analysis

The general trend is the slower is the growing phase of the fire, the longest is the ATSFR. This result was underlined for the case of the open space.

9.3.4.4 Early/late analysis

In the Table 17, the same results are presented in terms of early versus late detection using the concept presented in 9.2.4.3. Sensitivity to the *T* constant was studied using values ranging from 2 to 5 minutes. Positive results are obtained when the detection is considered early, the value indicates the margin. When the result is negative, the detection is considered late, the value indicating the delay.

Table 17: Simulation results for the closed space configuration in term of early vs. late smoke detection. Early detection is presented in green, late detection in orange

Scenarios			Criteria for early detection - 0 ≤ (ATSFR-RTSFR (2)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (3)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (4)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (5)) - s
Fire Growth	**Position of Fire**	**Ventilation**				
Slow	L3	Normal	497	437	377	317
Slow	L2	Normal	485	425	365	305
Slow	L1	Normal	500	440	380	320
Medium	L3	Normal	203	143	83	23
Medium	L2	Normal	232	172	112	52
Medium	L1	Normal	242	182	122	62
Fast	L3	Normal	35	-24	-84	-144
Fast	L2	Normal	52	-8	-68	-128
Fast	L1	Normal	42	-18	-78	-138
Fast	L2	Half	37	-22	-82	-142
Medium	L2	Half	232	172	112	52
Fast	L2	Double	53	-6	-66	-126
Medium	L2	Double	262	202	142	82

There is an overall good performance of the detection in the cases of slow and medium fire growths. Indeed, according to the definition of early/late based on the ATSFR criterion and assessing a constant between 2 and 5 minutes, all the simulations resulted in early detections.

For the case of fast fire growth, when the reaction time is above 2 minutes, it becomes late detection. This result was already underlined for the case of open space.

9.4 Risk models

9.4.1 *Main fire risk model*

For the purpose of specifically investigating the detection and decision nodes, the main fire risk model developed in FIRESAFE was reviewed and upgraded.

The main modification was the expansion of the former *Decision* node into two nodes, covering *Detection* and *Decision* respectively.

The definition of Early/Late Decision has remained the same as in FIRESAFE. “Early” and “Late” decision should be understood in relation to the fire growth rate. “Early” means that the Decision to activate the system has been taken early enough to have a chance to extinguish the fire. “Late” means that the fire is already quite developed, and that it is too late to have a chance to extinguish it. However, the fire can still be suppressed upon system activation.

The concept of *Early/Late detection* was also introduced (and was extensively discussed previously in Section 9.2)

As a consequence of the above-mentioned changes, a new additional node was also introduced focusing on first response. This part was previously included in the *Extinguishment* fault tree developed in FIRESAFE. The updated chain of events for FIRESAFE II is presented in Figure 32.

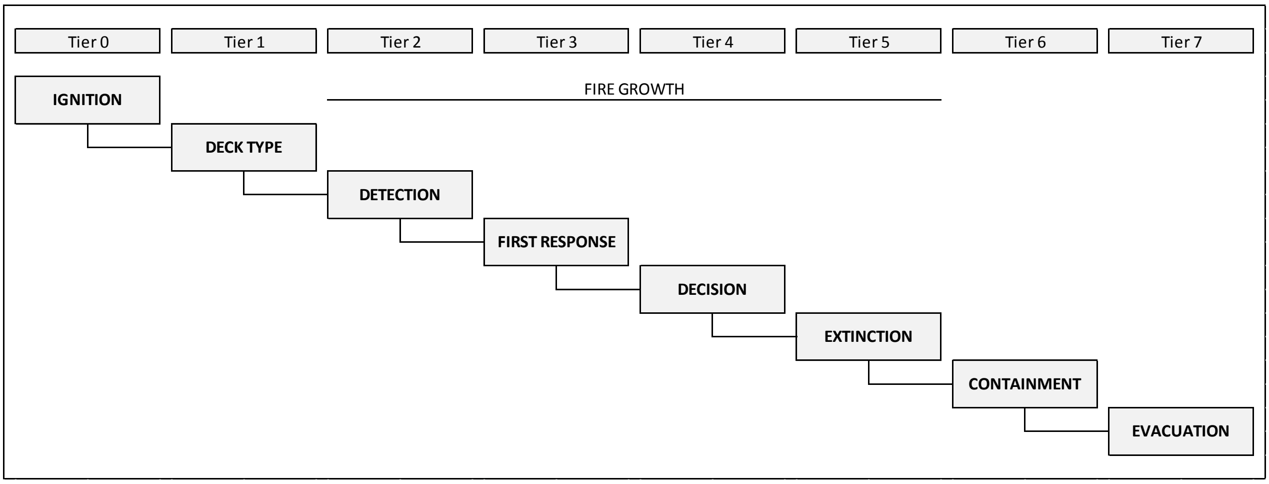

Figure 32: Updated chain of events for FIRESAFE II

As an illustration, the updated Main Fire Risk Model for the *Standard RoPax Newbuilding* (*Open ro-ro spaces* part only) is shown in Figure 33. The three parts (*Closed ro-ro spaces*, *Open ro-ro spaces*, and *Weather Deck*) are shown in the Annex A1.4. The event tree for the *Cargo RoPax* and the *Ferry RoPax* are provided in Annexes A1.3 and A1.5 respectively.

In addition, dedicated fault trees were developed for each generic ship (*Cargo RoPax*, *Standard RoPax* and *Ferry RoPax*) and potential differences between Newbuildings and Existing ships were taken into account in the detection and decision fault trees. This led to the development of 6 different risk models (*Cargo RoPax Newbuildings*, *Cargo RoPax Existing ships*, *Standard RoPax Newbuildings*, *Standard RoPax Existing ships*, *Ferry RoPax Newbuildings*, *Ferry RoPax Existing ships*). The structure of the trees were identical but the quantifications differed.

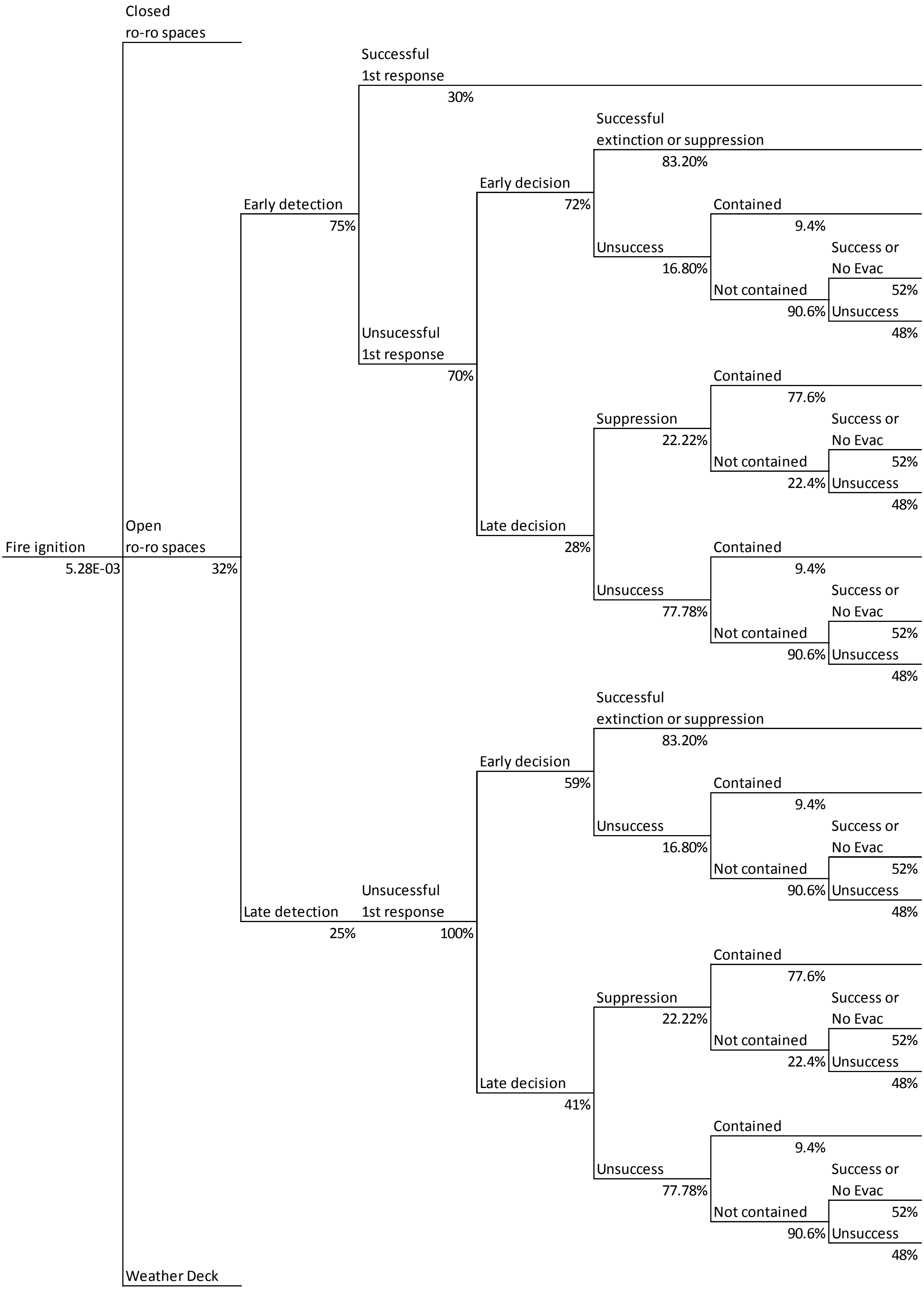

Figure 33: Updated Main Fire Risk Model for the *Standard RoPax Newbuilding* (*Open ro-ro spaces* part)

9.4.2 *Detection Fault tree*

A fault tree was developed to model early detection failure, meaning that unsuccessful first response is probable due to no or late detection. For *late detection* to occur, both *system detection failure* and *manual detection failure* are necessary. The failure probabilities are dependent on the deck type. While the structure of the tree remains the same for both closed and open ro-ro spaces, the quantification differs. In the absence of any fixed detection system on weather deck, the structure of the tree was adapted to model the early detection failure for this particular type of deck.

The structure and quantification of the fault tree for closed and open ro-ro spaces are illustrated in Figure 34 to Figure 36. In order to maintain readability, the fault tree was divided into two sub fault trees.

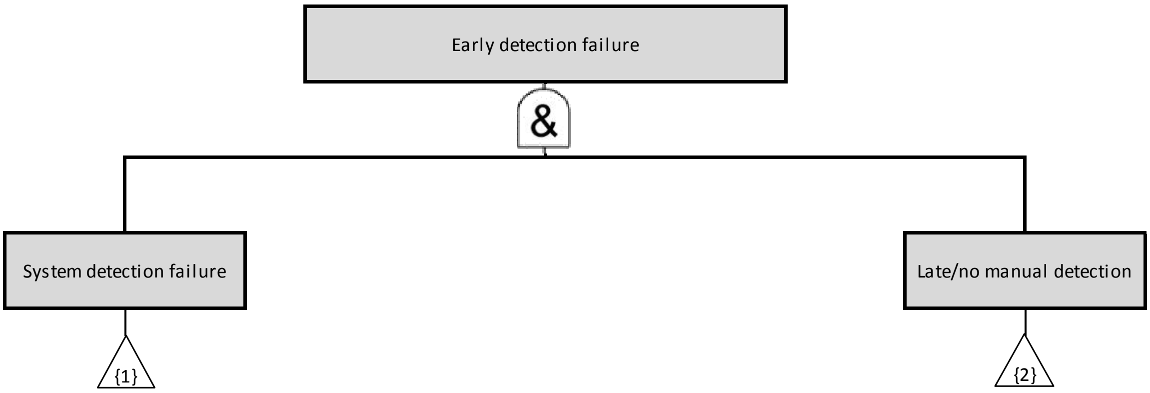

Figure 34: Detection fault tree (closed and open ro-ro spaces)

In order to populate the branches in the fault tree, and to remove the judgmental aspects of expert judgement, the 'expert information' approach (Skjong & Wentworth, 2001) was followed. The experts are asked for information and evidence, rather than for their opinions. Therefore, fire specialists, class society representatives and both on-shore and on-board personnel from ship operators were involved to provide information with a view of quantifying the tree. Simulations described in Section 9.3.1 also supported this discussion. Further description of the failures and considered factors for the estimates are provided in below sections.

9.4.2.1 System detection failure

System detection failure is divided into *internal failure*, which implies late detection despite favourable detection conditions, and *external cause*, which implies unfavourable detection conditions due to fire/sensor position, airflow or fire scenario. Estimates consider conventional point smoke detectors.

Internal failure:

- Manual deactivation

  Smoke detectors are generally deactivated during loading and discharging. The time in port versus time at sea varies greatly between different ships, generally from one out of 1:1 to 1:7. Statistics (based on 39 reported fires) indicate that one out of four fires occur while in port or just after leaving port.

  Detectors are also deactivated during work on deck if the work interacts with the detection system or if there is a risk of causing false alarms. In addition, a second alarm following e.g. a false alarm in another section, could be silenced and remain unnoticed due to combined specific actions on bridge and detection system arrangement (low probability).

Estimates only consider system failure, which means that any present personnel due to deactivated detectors is considered in the *manual detection failure* branch.

  - System

  Common that the complete system is deactivated (or at least a complete deck) when deactivated from bridge.

  - Individual detectors

  Individual detectors include a single detector or a section/part of a deck. However, it is unlikely that only a section is deactivated (sometimes not possible). A single detector could be deactivated/disassembled, however, due to surrounding detectors it is unlikely that late detection will occur.

- Technical failure

Technical failure includes all technical problems affecting the performance of the system or the sensors. Technical failures will generally result in a fault signal, which means that faults that could lead to late detection are considered to be fixed as soon as possible. A fault signal could be triggered e.g. by contamination of the smoke chamber, and this type of contamination is then considered as a technical failure. Other reasons could be power failure, signal failure or damage.

  - System

  Statistics on fire alarms on oil rigs (confidential source), indicate approximately 3% technical failures on system level resulting in an alarm (note: resulting in alarm signal, not fault signal). These failures (not causing a fault signal) are more likely to result in late detection due to unknown failures and extra time for troubleshooting. A fault signal is often associated with the type of failure.

  The failure probability only considers a part of all technical failures resulting in late detection during a fire. Most problems are solved in a short time.

  - Individual detectors

  The source from above indicates the same failure rate on detector level as for system level. However, due to surrounding detectors it is less likely that late detection will occur.

- Contamination or damage

Contamination of the smoke chamber of a detector due to e.g. dirt, dust or salt is common, but will most often cause fault alarms (classified as technical failure), false alarms or a more sensitive detector (earlier alarm). However, if dirt or dust blocks the detector openings or smoke inlet, it will cause late detection. Such failures can be hard to realize without frequent cleaning procedures. The extent of the contamination problem is large, since several ships use e.g. filter socks or shields to lower the amount of false alarms and fault alarms. In addition, basically all ships deactivate the detection system during loading and discharging due to the dirty environment.

Experience based, the contamination problem seems to be larger in open ro-ro spaces compared to closed ro-ro spaces, probably due to sea salt and other type of cargo.

Damage is primarily associated with deformation of detector cover, which prevents smoke to enter into the smoke chamber.

  - System

  Contamination or damage on system level (without fault signal) is rare, but is more likely to cause late detection if it happens. A dirty environment may contaminate all detectors on a complete deck, which is interpreted as system failure.

        - Individual detectors

          Individual detectors include a single detector or a section/part of a deck. Contamination will most probably affect a section or part of a deck, which is likely to cause late detection if not overhauled.

External cause:

It is assumed that early detection is achieved when deck and detection system is not affected by internal failures and there is no effect of below failure conditions.

The quantification of the *external cause* branch was supported by the exploitation of the results of the simulations.

- Poor detector position

  Poor detector positions consider cases where early detection would have been possible with a conventional smoke detector in another position of the detector in the deckhead.

    - Poor location

      Poor location is primarily affected by the (non-regulated) vertical position of the detector, which means how far in between ceiling beams the detector is located. Due to possible high cargo, it is preferred to have the detectors at the lower edge of the ceiling beams as the lowest position. Due to high airflow, smoke tends to not accumulate in between beams in the early stage of a fire.

      The distance between the detector and any other objects (e.g. beams) will also affect airflow around the detector, which might affect response time.

    - Poor spacing

      In case a fire at the largest horizontal distance away from a detector (with typical/regulated spacing) causes late detection, the spacing would be considered poor, provided that early detection is achieved at shorter horizontal distance between fire and detector. However, it is more likely that for most fire scenarios several detectors would initiate an alarm with fairly short time differences, meaning that poor spacing has low impact on *system detection failure*.

- Type of fire

  According to FIRESAFE, around 60% of the fires in ro-ro spaces are electrical fires, but there are plenty of other types of possible fires as well. Two types of fires that are assumed to be able to cause late detection are fires in *fuel producing small amount of soot* and fires with *too rapid fire development*.

    - Fuel producing small amount of soot

      Most fuels produce a lot of soot, especially solid fuels. Alcohol fires and gas fires generally produce less soot and some fuels, e.g. methanol, produce almost no soot (invisible flames). It is likely that a fire will involve several different fuels and produce a lot of soot, but there can be exceptions in the first stage of a fire involving e.g. an alcohol leakage.

    - Too rapid fire development

      A too rapid fire development in this case is defined as a fire growing beyond the threshold of possible first respond during the time interval between detection and fire confirmation by crew. Any liquid or gas fire has potential of growing too fast.

      According to FIRESAFE, there are 7.6% non-electrical fires related to the powertrain, in most cases probably involving some fluid or gas leakage.

- Fire position

  The fire position has great influence on the response time. *Fire inside cargo/vehicle* and *fire close to ventilation outlet/inlet* are considered to cause the most problem with respect to early detection.

- Fire inside cargo/vehicle

A fire inside an enclosed compartment can develop into a quite large fire before it is detectable (provided that enough oxygen is available). The size of the fire upon detection will result in first response failure.

According to FIRESAFE, there are 19% fires originating inside a cab.

- Fire close to ventilation outlet/inlet or openings

There is high risk that heat and smoke from a fire close to a ventilation outlet will be ventilated away, resulting in no detection when the fire is small. A fire close to a ventilation inlet can be affected by a locally higher airflow, resulting in more diluted smoke reaching the deckhead and possibly increased fire growth rate and faster fire spread.

Although the FSS Code stipulates that the detectors shall be located for "optimum performance" (FSS Ch. 9 §2.4.2) and that position close to beams and ventilation ducts where patterns of airflow could adversely affect the performance should be avoided, the lack of procedure for verifying this provision and the number of scenarios makes this failure realistic.

In open ro-ro spaces, due to more and larger openings, and the possibility of stronger winds, the failure rate is assumed higher on these spaces. This complies with operators' experience. Out of the 32 accidents reviewed, 2 cases of late detection due to the fire being close to large openings (on open ro-ro spaces) were reported.

- High airflow

The cargo free cross-sectional area of a deck affects the airflow at the detector, which might cause late detection. Conventional point smoke detectors rely on diffusion of the smoke from outside the detector to inside of the detector. With high airflow this process is slow, and smoke will be difficult to detect. Deck size, cargo size and loading configuration affect the cargo free cross-sectional area throughout the deck.

In addition, operator input indicates that early detection in combination with full mechanical ventilation might be difficult to achieve regardless of fire/sensor position or fire scenario.

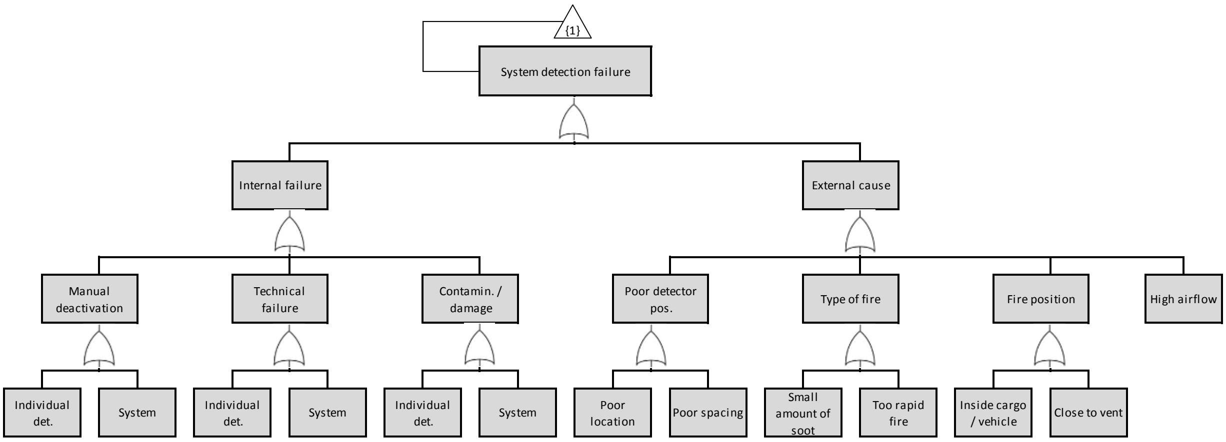

Figure 35: Sub-tree for *System detection failure* (Closed and open ro-ro spaces)

9.4.2.2 Manual detection failure

Manual detection failure is divided into *fire patrol failure*, which implies late or no detection by a designated fire patrol, *crew/passenger detection failure*, which implies late or no detection by passengers or crew members which is not part of the fire patrol, and *detection failure from bridge*, which implies no deck view from bridge or late visual detection of fire from the bridge.

Fire patrol failure:

Either the fire patrol is *not present* or the fire patrol is non-efficient (*quality failure)*.

- Not present

  Not present implies that the fire patrol is not in place to be able to detect the fire or that the fire is detected too late, which means that probable safe first response cannot be achieved. (The fire patrol is assumed to always take first response if possible).

  The reason why the fire patrol is not present at the early stage of a fire is either *low frequency* of fire patrols (scheduled) or that the fire patrol is skipped/shortened for other reasons (*required but still not present*).

  - Low frequency

    Fire patrol frequency varies with different ships. However, a general time interval of one hour between fire patrols was taken as the reference for this study.

    The time interval from a detectable stage of an incipient fire (or thermal event) and a fire possible to extinguish with a first response approach, varies greatly with the fire scenario. A smouldering fire may exist for minutes-hours, with high probability of being detected in this stage.

    With a medium growth “T-squared” fire (considered to be the expected fire growth for ro-ro space fires according to FIRESAFE), the above time interval would be approximately 6-7 minutes. However, this is considered conservative as the incipient stage (e.g. a smouldering fire) is not included in this duration.

    Detailed descriptions of the assumptions taken for the quantification of this node are provided in section 10.5.5.

  - Required but still not present

    The reason why a fire patrol is skipped or shortened can be due to high workload/another priority or just low motivation. Low motivation can be due to physical attributes (e.g. tired/fatigued) or social attributes (e.g. preferred coffee break instead of patrol).

    For failure, there must be both low motivation and lack of controls. Control systems are often based on checkpoints that must be registered during a fire patrol. It is assumed that a low part (<10%) of the world fleet have control systems. There are also differences in the efficiency of the control system, e.g. number of checkpoints and how checkpoints are registered. It could also be debated whether checkpoints contribute in an unproblematic way to detection. With any highly repetitive work task you will run the risk of the person simply going through the motions without paying attention to the surrounding environment. Checkpoints ensure that the person is present physically but he/she is not necessarily present mentally. It could even be that the task of identifying and checking off the checkpoints becomes a distraction from the actual search task

- Quality failure

  The quality failure implies that the fire patrol is present but does not detect a small fire (incipient stage) due to *accessibility problems*, *lack of training/experience*, *lack of suitable equipment* or *low motivation*.

- Accessibility problems

  Accessibility problems are most often caused due to cargo. It is high probability that fire patrols will only walk along walkways, sides or casings of the ro-ro spaces. However, also small fires can be detected by the smell or sight of smoke.

  There might also be problems with accessibility to other smaller rooms/enclosures adjacent to the ro-ro spaces (very low probability).

- Lack of training/experience

  Lack of training/experience will affect the act of fire patrols, e.g. chosen patrol routes on a ro-ro space, knowing what to look for and to focus on certain risk areas.

- Lack of suitable equipment

  Suitable equipment related to fire detection is for example gas sniffers and infrared (IR) cameras (there are other suitable equipment for fire patrols related to e.g. successful first response). It should be noted that none of them are required as per SOLAS.

  The human nose is very sensitive, and the added value of a gas sniffer can be limited. In addition, strong odorants are added to most gases used as alternative fuels in vehicles. However, hydrogen and methanol used in fuel cell vehicles are generally odourless and cargo might as well contain certain odourless gases.

  The IR camera can be used to detect hot spots which might turn into a fire eventually. Good training and experience is probably needed to give value, and the most common procedure would probably be to use the camera after a suspicion already has been raised (e.g. due to smell, hearing a miss sound, seeing a connection that does not look right, or sensing abnormal heat when passing a vehicle/cargo.) IR camera also allows to investigate areas not reachable for the patrol due to height or access.

- Low motivation

  Low motivation can be due to physical attributes (e.g. tired/fatigued or stressed due to high workload) or social attributes (e.g. focus on conversation between crew members). No matter the reason for low motivation, it will cause distraction and less efficient fire patrol.

Crew/passenger detection failure:

Although they are not expected to be part of the detection system as a whole, passengers or crew (who is not part of a fire patrol) are likely to give the alarm in case of fire. In that sense, a failure of detection by crew/passenger can be considered as an additional failure mode. (However, it is assumed that they will not always take first response even though it would be possible. It is also assumed that a passenger or crew member (not part of a fire patrol) will consider a smaller fire as not “extinguishable” by means of first response than a trained crew member part of the fire patrol would consider.) Several reasons can lead to detection failure by the crew/passenger. The most obvious is that they are *not present in the space* where the fire is occurring, or that they are present in the space but too far away to have an early detection of the fire. They can also be present but still fail to detect (report) early.

- Not present

  As the crew/passenger are not expected to be part of the detection system as a whole, it is very unlikely that they will be present on deck at the time of a fire (they may even not have access to some decks). However, it may be the case during loading or discharging. The quantification of this node is dependent on the turnaround time of the vessels (4h of cargo handling for a 26h voyage for the *Cargo RoPax*, 4h of cargo operations for a 9h voyage for the *Standard RoPax*, and 1.5h of cargo operations for 2.5h of voyage for the *Ferry RoPax*).

  Note that this failure estimate is highly dependent on the “manual deactivation” estimate (system detection failure). The probability that crew is present when the detection system is deactivated is high (loading/discharging and work on deck) and the probability is low when the system is activated (e.g.

regulations do not allow passengers on deck while at sea). The presented average should therefore be used with some caution.

It is estimated that there is high probability that some lower decks (roughly 1 of 5) could be left unattended half of the loading time (while still loading upper decks) and with deactivated detection system for all decks.

- Present in the space but too far away

The crew/passenger may also be present on deck (e.g. during loading/unloading), but too far away from the seat of the fire to be able to detect it early.

- Present but fail to report

They can also be present but still fail to detect (report) early due to:

  - Unwilling to report

  Unwillingness can be due to e.g. guilt or poor safety culture. For instance, if a crew member is told there is a fire he/she might wait to communicate until he/she is certain that the information is correct (poor safety culture).

  Unwillingness can also be due to either guilt (e.g. person has caused the fire or person should not be present on deck) or uncertainty whether this will sound an alarm throughout the ship.

  - Communication failure

  Communication failure can occur for example due to technical failure (e.g. manual call point failure or radio failure), poor markings (eventually in combination with too far distance to the call point), or lack of knowledge on how to report a fire in the absence of a crew member.

Detection failure from bridge:

Detection failure from bridge implies that bridge personnel fail to be the first one to detect a fire such that early detection is met. Failure is caused either due to no direct view of deck or no CCTV view, or in case of possible view, no one looking or no one detecting the fire due to e.g. distance and obstructing cargo.

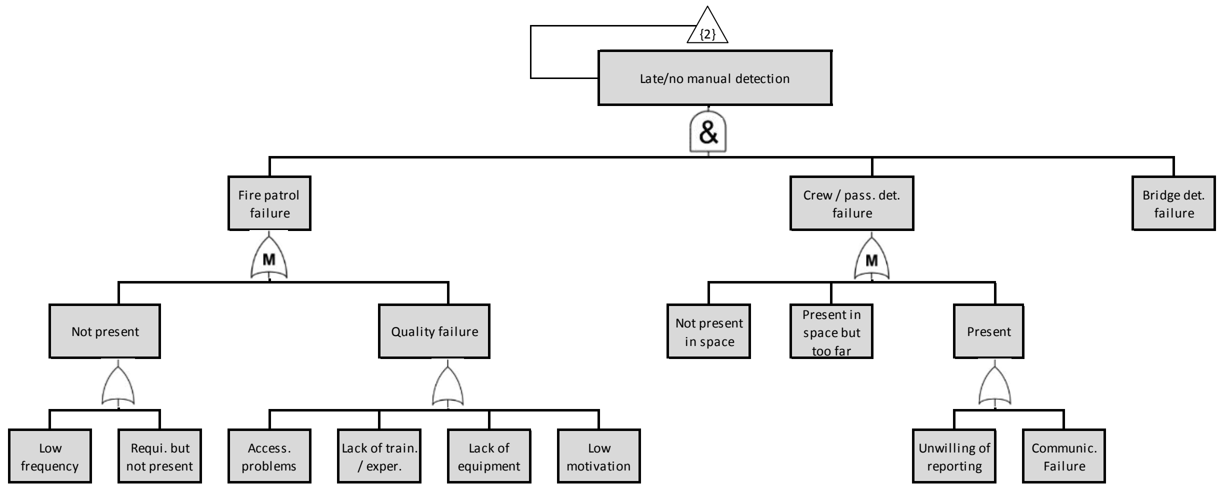

Figure 36: Sub-tree for *Late/no manual detection* (closed and open ro-ro spaces)

9.4.3 *Early detection failure rate*

The development and quantification (provided in details in Annex A1.6) of the above fault trees allowed the quantification of the overall Early detection failure rate for each of the generic ship categories. This figures are provided in Table 18.

Table 18: Probability of Late detection according to the type of ro-ro spaces for each ship category for both Newbuildings and Existing ships. 90% confidence interval is indicated in square brackets

	Closed ro-ro space	Open ro-ro space	Weather deck
Cargo RoPax	28.4% [21.8%; 35.7%]	N/A	68.2% [59.9%; 76.0%]
Standard RoPax	23.8% [17.7%; 30.7%]	24.7% [18.5%; 31.6%]	57.8% [48.3; 67.3%]
Ferry RoPax	23.9% [18.0%; 30.4%]	N/A	58.2% [49.7%; 66.8%]

The overall probability of detection failure was estimated to approximately 25% in closed ro-ro spaces for all ships: 28.4% for the *Cargo RoPax*, 23.8% for the *Standard RoPax* and 23.9% for the *Ferry RoPax*. The differences in the probabilities could be explained from the different turnaround time for the vessels, which in turn has an impact on the Crew / Passenger detection failure. This difference is more visible on weather deck where there is no fixed fire detection system.

The probability of late detection in a closed ro-ro space due to a technical system failure is identical for all ships.

Due to the possibility for the smoke and heat to be ventilated away due to the large openings in the ship sides, there is a higher chance of early detection failure in open ro-ro spaces (24.7%) compared to early detection failure in closed ro-ro spaces (23.9%).

None of these probabilities are affected by the keel laying date of the vessels (i.e. no difference between newbuildings and existing ships).

Uncertainty analysis on the probability of late detection was performed (methodology followed is detailed in section 12.5 and Annex A2). The estimated confidence intervals are reported in Table 18 and an illustration of the late detection probability distributions for the *Standard RoPax* Newbuildings is provided in Figure 37.

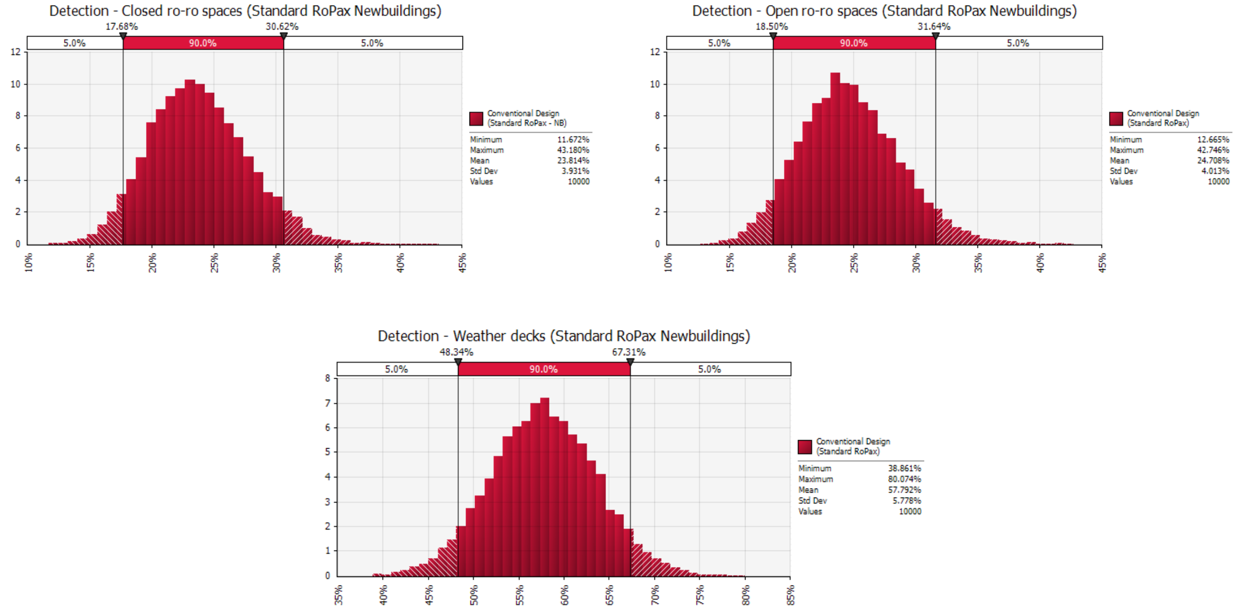

Figure 37: Distributions of the probability of late detection on Closed ro-ro spaces, Open ro-ro spaces and Weather decks of the Standard RoPax Newbuildings

9.4.4 *Decision Fault tree*

This chapter contains a plain text account of the fault tree for decision-making in the event of a ro-ro space fire, developed jointly by the FIRESAFE II partners. This fault tree covers decision-making, with a focus on bridge activities, from the point where the bridge receives a fire alarm up to the point where a decision is taken about fire response.

9.4.4.1 Method

The fault tree for decision-making is based on data from the HazId, the review of past ro-ro space fire incidents and data from observations on-board a Swedish RoPax ship, all reported in previous chapters. The decision was made to confine the tree to activities leading up to the actual response, thus reflecting the aims of the overall study.

Human factors specialists from RISE created a first draft structure of the fault tree which was then revised iteratively in collaboration with the other partners, exploring background factors or upstream conditions for the potential errors that had been identified.

In the next step, expert judgment was acquired of probabilities for the bottom nodes of the tree, taking into account the potential difference between newbuildings and existing ships, as well as the different types of ships. Additional data was gathered from the COREDATA (Kirwan, Basra, & Taylor-Adams, 1997) human error database and used for comparison. After this, the trees were reviewed for node relationships. As the decision is affected by the detection time, a different quantification is provided for an Early Decision failure following an early detection and a late detection.

Taking into account the absence of fixed fire detection system in the weather deck, specific fault trees were developed to model an Early Decision failure following a fire detection on the weather deck.

It should be pointed out that the fault tree for decision-making was developed with close consideration to the data collected through different subtasks, i.e. one HazId activity, one instance of observations/interviews and a review of past ro-ro space fire incidents. Many more background conditions could potentially contribute to any node in the tree, but the represented conditions are those where direct support was found in the available data.

9.4.4.2 Results

This section explains the contents of the fault tree which is shown in Figure 38 to Figure 41. The scope of the decision-making task and the time criticality of early decisions in the event of a ro-ro space fire led to the selection of *Late decision to respond* as top node. Three major aspects were found to contribute to this late decision: *Late alarm interpretation*, *Late confirmation* and *Late assessment*, each one presented and explained in the following sections. These are activities that are either direct parts of the decision-making process or that provide information that is essential for decision-making to be possible.

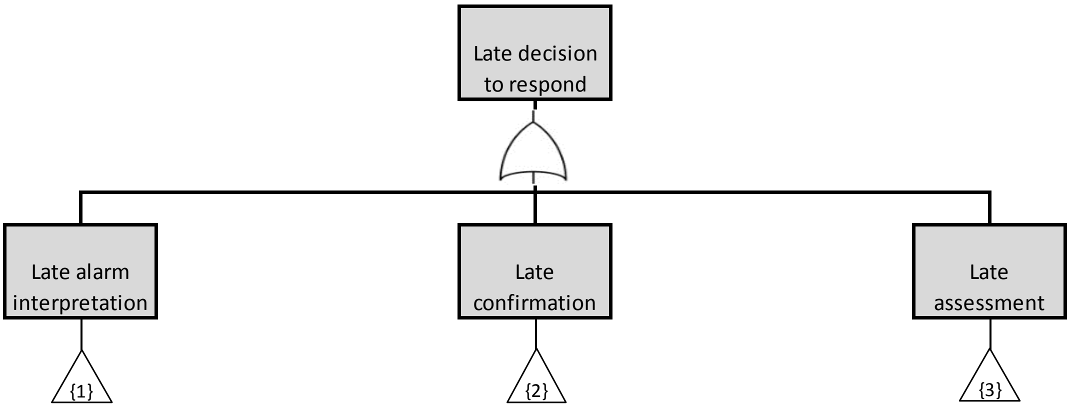

Figure 38: Decision fault tree (Closed and open ro-ro spaces)

9.4.4.2.1 Late alarm interpretation

When a fire alarm arrives on the bridge, the information has to be interpreted so that the first decisions can be made, typically around the confirmation of fire. Making sense of the alarm may however be challenging due to a number of different causes.

First, an incoming alarm may be dismissed as false, for example if the operational state is such that a natural cause for the alarm can be imagined. For some bridges, false alarms are common and frequent false alarms may come to undermine the vigilance and decisiveness of the crew. In order to minimise nuisance alarms, it is common practice to disable the alarm system during loading and unloading, a solution associated with problems of its own. An alarm may also be interpreted as normal, for example if there are known maintenance activities in the indicated area. On the other hand, discussions within FIRESAFE II have given that alarms on ro-ro spaces are always likely to be treated seriously, since most people working in these environments know of the potential catastrophic consequences of such a fire. That being true, false alarms will always weaken the effectiveness of the overall system and, according to an informant, even newly built ships are not immune to the existence of false alarms.

Second, alarm interpretation may be late because of delays in alarm handling. One possibility is that the alarm is missed altogether, for example due to a failure of attention. This scenario is deemed unlikely by experts, but one possibility may be that additional alarms are missed (i.e. fire spread) for example due to muting. On some bridges, different alarms and their respective signals may be poorly integrated producing a difficult environment for communication, prompting the crew to mute alarms immediately. As another example, one system was observed where the opening of a protective glass hatch in front of the alarm panel would automatically mute the alarm signal on the bridge, which would stay muted (even for additional alarms) as long as the hatch was open. Within the scope of FIRESAFE II, however, it has not been possible to review usability in alarm systems on a more general scale.

A more commonly reported cause of delays in alarm interpretation is the need to integrate different pieces of alarm information. First, most ships alarms are not addressable down to an individual detector, although detector looping can improve the situation. Despite this, the person receiving the alarm will often be forced to integrate data such as section number, drencher section and valve number to understand the most probable location of the fire. One possible cause of problems like these is that system usability is not preserved when changes are made to the ship, e.g. rebuilds such as changes in sectioning. Moreover, the information about the fire location presented to the receiving person can be difficult to interpret, at least in a stressed situation. Competence e.g. experience and familiarity with the ship environment can also play a part in this problem. For example, during night-time operations the watch may be held by a junior member of the crew.

Third, it was noted that the different systems needed to assemble a complete picture of the alarm situation may be scattered across the bridge. A ship’s bridge will often transform through the years due to new needs and requirements, and changes may run the risk of breaking up the original logic for alarm panel layouts and placements. Some time may be lost due to the simple need to move across the bridge in order to assemble all the relevant information around the alarm, but more importantly, time lost in movements will make it harder for the person on the bridge to remember information that needs to be integrated, demanding double checks that cause unnecessary delays in alarm handling.

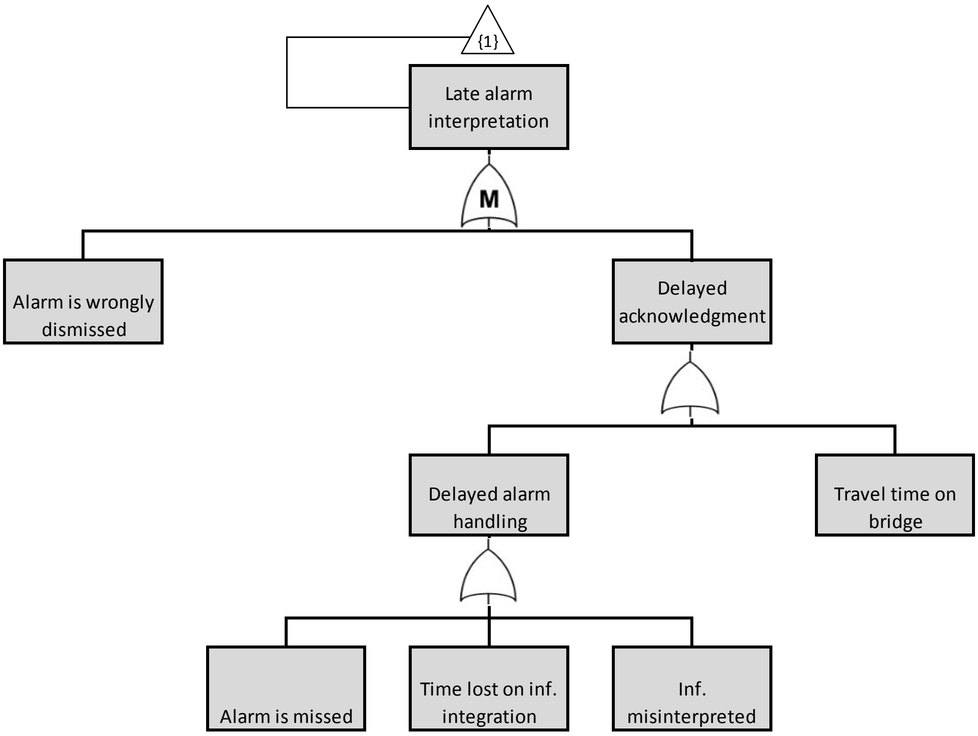

Figure 39: Sub-tree for *Late alarm interpretation* (Closed and Open ro-ro spaces)

9.4.4.2.2 Late manual confirmation

When the fire alarm has been received and interpreted, the next step is to manually confirm the existence and exact location[18] of the fire. Information collected in FIRESAFE II suggests that the most common practice is to deploy a “runner” to the detector point (an action limited by the precision of the indication) whom will then report to the bridge and, in cases of very limited fires, extinguish directly with a hand-held extinguisher. It was pointed out that not all shipping companies employ this practice, e.g. because the alarm system information is taken as confirmation enough to deploy fixed suppression system and make fire party prepared. At some point, however, experts seem to agree that direct assessment from a person or persons at the fire scene is necessary. However, this also introduces a risk that the person making assessment is injured by smoke and in worst case passes out in the area close to the fire which calls for rescue by the fire party in a later stage (this is a challenging task and removes focus from firefighting to favour search and rescue).

First, deployment of the runner may be delayed, either because there is no decision-maker immediately present at the bridge to make the deployment decision, or that the alarm information is erroneously interpreted to mean that no confirmation is necessary (e.g. a false alarm scenario), or that no crew member is immediately available to go, for example because of other pressing tasks or due to the crew being temporarily reduced (e.g. during night-time operations).

Second, the runner may be delayed on his or her way to the point of detection. This may be due to a complex route caused by the basic design and layout of the ship, a problem that may be aggravated by poor guidance in the form of markings, signage, plans and instructions, insufficient familiarisation with the ship or that available crew members happen to be situated far from the point of detection. Two other contributing factors were identified. Low motivation in the event of a ro-ro space fire alarm is deemed unlikely, but motivation may suffer if the crew member perceives him/herself to be poorly equipped for the task (e.g. sent to the location dressed in regular, flammable clothes), impacting both the time to get to location and subsequent

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[18] Exact location: Order of magnitude of 20m (1 drencher section)

effort for attempting to put out a fire. Fitness has also been mentioned as a factor for long travel time, although this appears to be a less common problem.

When the runner arrives at the point of detection, the person has to identify the exact location of the fire[19]. It might appear that a fire on deck should be obvious given that smoke or heat has actually been detected technically, but deck ventilation may conceal the smoke plume also making it harder to smell of the fire, and cargo obstructing visibility on the deck can make the task of localisation more difficult. Next, effective localisation demands the runner to systematically search the deck and assess the situation, an activity where the strategy and thoroughness may be affected by stress, the person's experience, training and familiarity with the ship. Finally, localisation of the fire may be delayed because of poor support, either in the way of procedures or a lack of technical equipment to aid the search.

When the fire has been located, observations must be relayed back to the bridge for the next phase of decision-making. Communication is often pointed out as a common cause of delays and errors in shipboard fire management, both by FIRESAFE II experts and in accident investigations. This instance of communication may be impeded by a lack of communication equipment or that the equipment available has poor coverage, forcing the runner to move to an area with better reception or to a fixed phone. There is also a risk of misunderstandings when the runner communicates fire related information, for example due to unclear section numberings and signage or that the crew lacks a shared vocabulary. Communication may also be delayed because of social dynamics (e.g. strict hierarchies or divides between bridge and engine personnel), although circumstances like these will likely tend to be of less importance in the case where a runner has explicitly been sent to relay information back to the bridge.

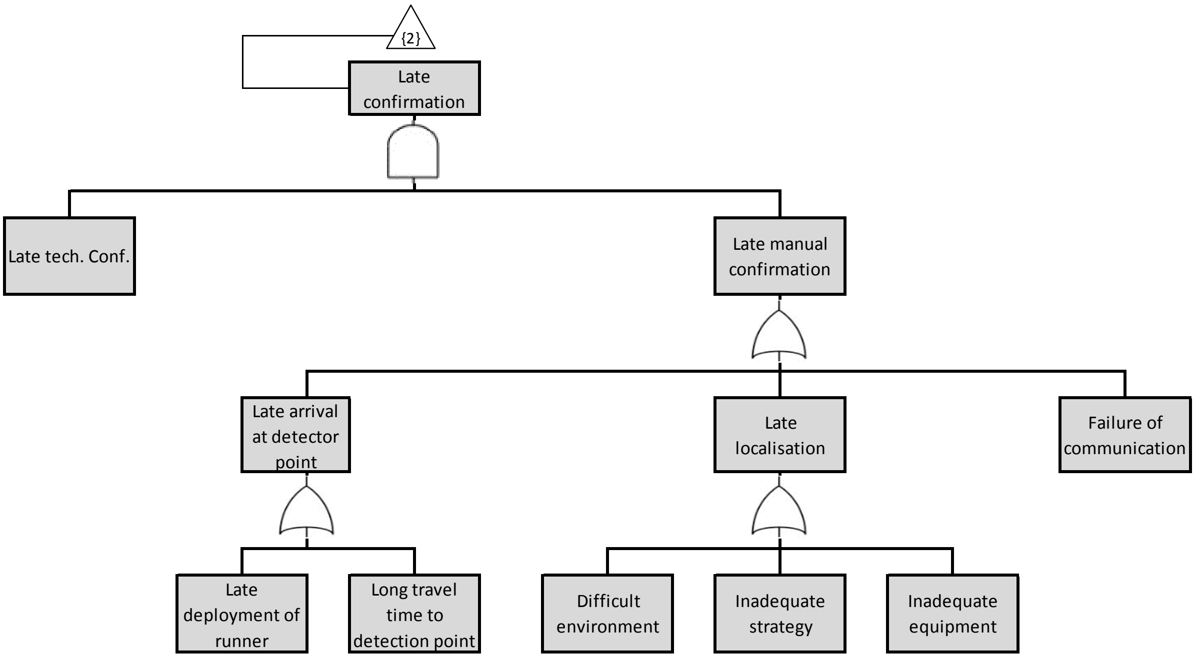

Figure 40: Sub-tree for *Late confirmation* (Closed and open ro-ro spaces)

9.4.4.2.3 Late assessment

Based on initial information from the fire scene, the decision-maker on the bridge has to assess the situation and choose a response strategy, typically to activate a fixed extinguishing system, to order a manual fire-fighting operation or both. Data describes three sets of circumstances that might delay assessment.

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[19] This applies to small fires that can be put out manually but not to fires that generate a lot of smoke or large fires, where the drencher should be directly activated instead of attempting a manual first response. If the runner finds no signs of fire in the area, then the exact location becomes important to be able to say with confidence that there is no fire.

First, in order to make a proper assessment, the necessary competence and experience has to be present. This may be less likely under certain circumstances, such as night-time operations when persons in command positions (working on daytime schedules) have gone to bed. The operational state may also affect the availability of key personnel for situation assessment, for example if the ship is in a position demanding the direct attention of the crew (e.g. narrow passages, large amounts of surrounding traffic, manoeuvring in harbours, other technical issues e.g. in the engine). In some cases, delays may also be caused by the distance to the bridge for relevant personnel.

Second, assessment can be delayed if time has to be spent searching for information about vehicles and cargo around the fire scene. According to experts, cargo information is not essential in order to make the decision about first response, but the presence of AFV is one piece of information (seldom available) that may be relevant for this phase of decision-making.

Third, a lack of competence of the bridge personnel around a ro-ro space fire scenario may cause further delays in situation assessment. All Officers and Masters have formal training in fire management, but according to project informants, the way in which recurring exercises and drills are arranged and implemented varies greatly between shipping companies, and sometimes even between ships belonging to the same company. For example, the degree of realism in terms of situation complexity, interactions, communication and context may affect the actual ability of the crew to make decisions under real-world conditions.

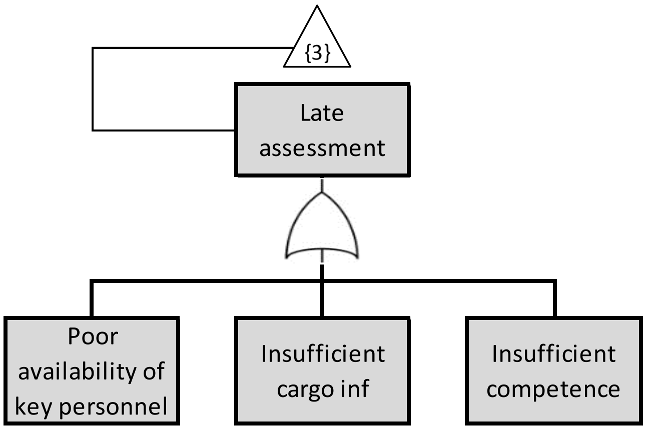

Figure 41: Sub-tree for *Late Assessment* (Closed and Open ro-ro spaces)

9.4.4.2.4 Differences for Late Detection

The scenario for late detection of fire in the ro-ro deck (implying a more developed fire) has consequences for the decisions and actions of the crew. For that reason, a separate quantification was developed (and reported in Annex A1.7) and the differences are described below. In the case of a more developed fire, all nodes representing loss of time are aggravated due to less time being available overall.

The larger amount of information available on the bridge (e.g. more alarms) in the case of a larger fire causes a higher quantification for the nodes “time lost on information integration”, “Information misinterpreted” and “Travel time on bridge”. At the same time, the risk of “Alarm is wrongly dismissed” (e.g. confusing alarms with natural occurrences on deck) is viewed as negligible compared to a less complex alarm situation.

The role of the runner is still deemed relevant for this scenario but the nodes “late deployment of runner” and “long travel time to detection point” receive a higher quantification because of less time being available. For localisation of the fire, “Difficult environment” is increased because of increased smoke and heat while “Inadequate strategy” and “Inadequate equipment” are reduced since there will be no opportunity to employ them. Lastly, “Failure of Communication” increases because of increased duress and the need of communicating more information.

On the bridge, “Poor availability of key personnel”, “Insufficient Cargo Information” and “Insufficient Competence” are increased due to the more demanding situation requiring more experience and information.

9.4.5 *Early decision failure rate*

The development and quantification (reported in Annex A1.7) of the above fault trees allowed the quantification of the overall Early decision failure rate for all ship categories, for both Newbuildings and Existing ships. These figures are provided in Table 19 and Table 20 respectively.

Table 19: Probability of Late decision according to the Detection time, type of ro-ro spaces for each ship category for Newbuildings

	Detection time	Closed	Open	Weather
Cargo RoPax	Early	27.8% [17.1%; 43.2%]	N/A	19.3% [9.9%; 33.7%]
	Late	40.7% [28.1%; 56.2%]	N/A	30.0% [18.7%; 45.5%]
Standard RoPax	Early	27.8% [17.1%; 43.2%]	27.8% [17.1%; 43.2%]	19.3% [9.9%; 33.7%]
	Late	40.7% [28.1%; 56.2%]	40.7% [28.1%; 56.2%]	30.0% [18.7%; 45.5%]
Ferry RoPax	Early	27.8% [17.1%; 43.2]	N/A	19.3% [9.9%; 33.7%]
	Late	40.7% [28.1%; 56.2%]	N/A	30.0% [18.7%; 45.5%]

As explained in paragraph 9.4.4.2.4, the overall probability of decision failure is dependent on the detection time. For both closed and open ro-ro spaces, the early decision failure rate was estimated to 27.8% following an early detection and 40.7% following a late detection for the *Cargo RoPax*, *Standard RoPax* and *Ferry RoPax*.

Since the detection is performed manually on the weather deck, which implies that a crew member is already close to the seat of the detected fire, the probability of late decision on a weather deck is lower: 19.3% following an early detection and 30.0% following a late detection.

This probability of late decision is lower on the closed and open ro-ro spaces of Newbuildings due to the reduced time in information integration provided the individual addressability of the detection system. However, this does not affect the probability of late decision on the weather decks.

Table 20: Probability of Late decision according to the Detection time, type of ro-ro spaces for each ship category for Existing ships. 90% confidence interval is indicated in square brackets

	Detection time	Closed	Open	Weather
Cargo RoPax	Early	28.6% [17.5%; 44.1%]	N/A	19.3% [9.9%; 33.7%]
	Late	42.0% [28.6%; 57.8%]	N/A	30.0% [18.7%; 45.5%]
Standard RoPax	Early	28.6% [17.5%; 44.1%]	28.6% [17.5%; 44.1%]	19.3% [9.9%; 33.7%]
	Late	42.0% [28.6%; 57.8%]	42.0% [28.6%; 57.8%]	30.0% [18.7%; 45.5%]
Ferry RoPax	Early	28.6% [17.5%; 44.1%]	N/A	19.3% [9.9%; 33.7%]
	Late	42.0% [28.6%; 57.8%]	N/A	30.0% [18.7%; 45.5%]

Uncertainty analysis on the probability of late decision was performed (methodology followed is detailed in section 12.5 and Annex A2). The estimated confidence intervals are reported in Table 19 and Table 20 and an illustration of the late decision probability distributions for the *Standard RoPax* Newbuildings is provided in Figure 42.

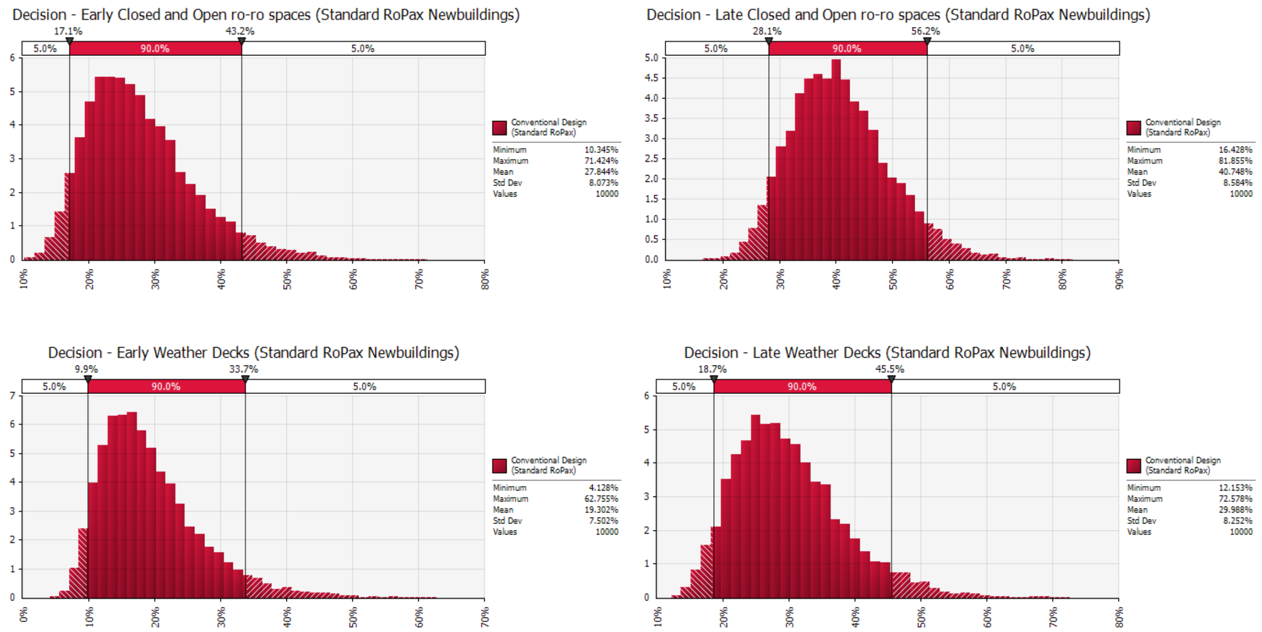

Figure 42: Distributions of the probability of late decision on Closed ro-ro spaces, Open ro-ro spaces and Weather decks of the Standard RoPax Newbuildings

9.4.6 *Review of the other nodes*

9.4.6.1 Ignition

The Ignition node is extensively elaborated in the FIRESAFE report (EMSA, 2016). The initial accident frequency was updated based on the findings described in section 8.1.2. The frequency of fires in ro-ro space was estimated to 5.28E-03 fires in ro-ro spaces per shipyear. However, the apportionment of fire causes was kept identical to FIRESAFE.

9.4.6.2 Deck type

The *Closed ro-ro spaces* / *Open ro-ro spaces* / *Weather Deck* proportion varies according to the specific design of the ships. As in FIRESAFE, it was assumed that the risk of ignition is evenly distributed on the different decks, i.e. the probability of fire ignition on a given deck configuration is considered to be proportional to the size of the deck. This is correlated to the amount of cargo transported on that deck and also to the amount of equipment.

The deck type repartition for each of the generic ships was provided in section 7.5.2.

9.4.6.3 First response

As first response was out of the scope of this study, the figure found in FIRESAFE for *First response failure* (following an *Early detection*) was kept and no specific fault tree was developed. By definition, first response failure after a *Late detection* was set to 100%.

9.4.6.4 Extinguishment

The Extinguishment node was investigated in detail in the first FIRESAFE study (EMSA, 2016). As the focus of FIRESAFE was on the failure of the fixed fire extinguishing system, the branch *Weather Deck* was collapsed.

In FIRESAFE II, the findings from FIRESAFE were used to quantify the *Closed ro-ro space* and *Open ro-ro spaces* branches of the event tree. Failure of fire extinguishment on weather deck was set to 70% following an *Early Decision* (finding from FIRESAFE) and to 90% following a *Late Decision*.

9.4.6.5 Containment and Evacuation nodes

The Containment and Evacuation nodes were investigated into details in a dedicated part of FIRESAFE II (EMSA, 2018). The findings from this part were used to quantify the event tree.

9.4.6.6 Consequences

The findings of FIRESAFE (EMSA, 2016) were kept to populate the consequence part of the risk model. While the variety of outcomes was recognized, an average value for the number of fatalities is sufficient to calculate a Potential Loss of Life (PLL).

A fatality rate of 8% of the Persons On Board was hence used to calculate the average fatalities following the scenario: fire on vehicle deck / escalation / unsuccessful evacuation. When evacuation is successful, a 1 equivalent fatality fixed value was assigned to take into account the frequent injuries and possible indirect fatalities following such evacuation. No fatalities were considered in the other cases.

Consequences for property (cargo and ship) were also discussed in FIRESAFE and the same values were assumed in FIRESAFE II for the purpose of calculating the Potential Loss of Cargo (PLC) and Potential Loss of Ship (PLS). The consequences following a fire put out by the crew (manual first response) was considered identical as a fire detected early and put out by means of the drencher system.

9.5 Risk quantification

Based on the risk model described above, the Potential Loss of Life were compiled for the three vessel categories (Newbuildings and Existing ships), as presented in Figure 43.

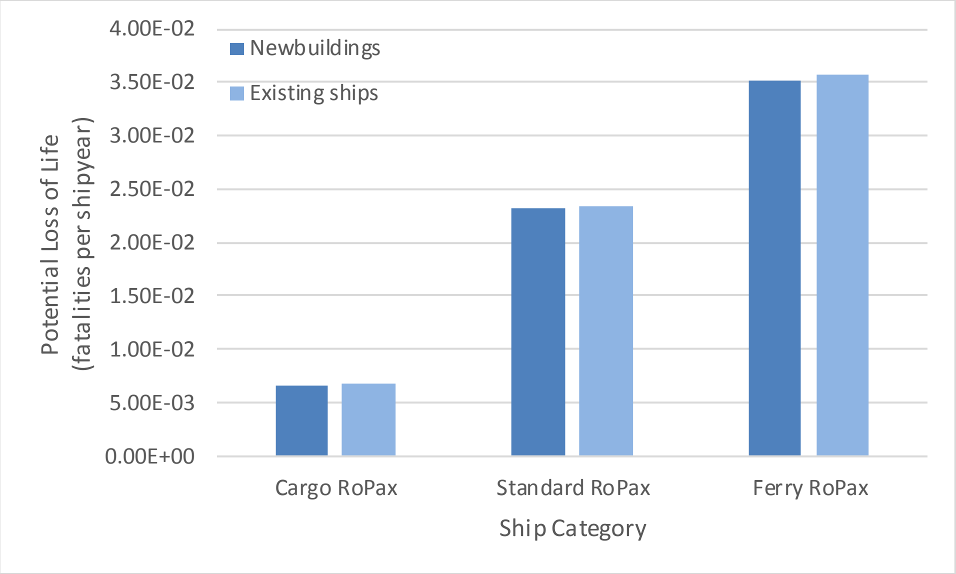

Figure 43: Potential Loss of Life (PLL) for the three generic ships considered

In comparison with the PLL derived from historical data reported in section 8.1, the PLL figures derived from the event risk model are lower. Although the consequence part of the main fire risk model was developed to be representative of the average consequences of accidents, it should be noted that a single accident leading to a high number of fatalities within a limited period in time may skew the estimated historical societal risk. This may create a difference between the estimated historical societal risk and the risk estimated with the risk model. Furthermore, the number of passengers onboard the Al Salam Boccaccio 98 at the moment of the accident exceeds the passenger capacity of the *Ferry RoPax* considered in this study.

It should be noted that the PLL of the *Cargo RoPax* is much lower than the PLL of the *Standard RoPax* and *Ferry RoPax* mainly due to the low passenger capacity of the *Cargo RoPax*. A low difference between the PLLs for Newbuildings and Existing ships was found, mainly due to the fact that the only difference considered in this study is the non-addressability of the detection systems on *Existing ships*.

In addition to the risk to human life, the risks to the property (cargo and ship) were considered. The Potential Loss of Cargo and Potential Loss of Ship were estimated and are presented in Figure 44. Similar to the first FIRESAFE study, no differences in the ship damages were considered between Existing ships and Newbuildings.

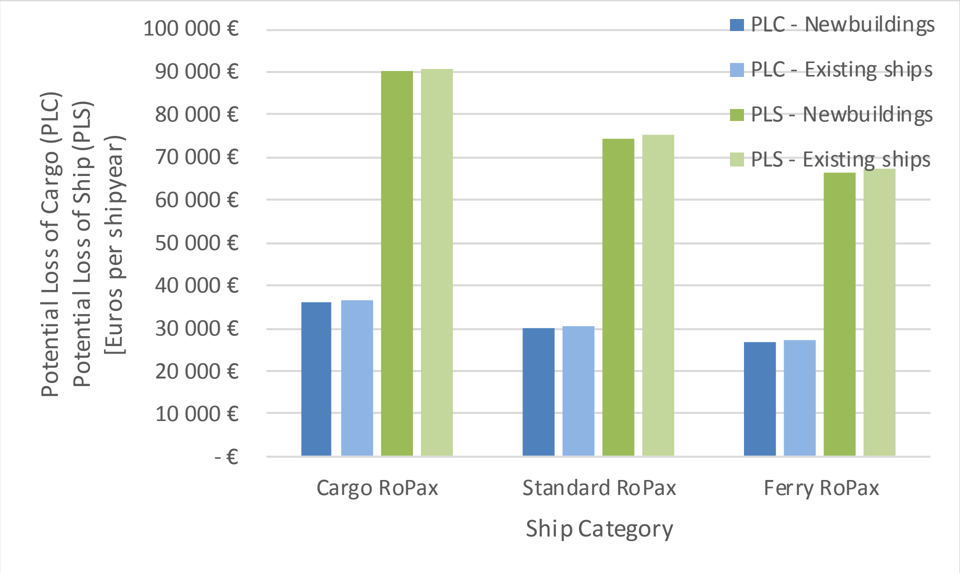

Figure 44: Potential Loss of Cargo (PLC) and Potential Loss of Ship (PLS) for the three generic ships considered

10 RISK CONTROL OPTIONS - DETECTION

To propose effective and practical risk control options (RCOs) for further evaluation, the following stages were considered:

- Focusing on risk areas requiring control;
- Identifying potential risk control measures (RCMs);
- Evaluating the effectiveness of the RCMs;
- Group RCMs and select suitable RCOs for further cost-effectiveness analysis (CEA).

Early detection of fires in ro-ro spaces is very important for fire mitigation. Early fire detection, including means of detection, communication and alarm procedures, might fail in many aspects. This was discussed during a hazard identification workshop, where risk control measures were also identified. Structured analysis in several workshops comprising experts from fire research, classification society and industry led to the selection of a limited number of RCOs, evaluated more deeply.

10.1 Identification of RCMs

For the detection part, a range of Risk Control Measures was identified based on the hazards identified in previous steps and on proposals of RCMs identified in former projects. The list of RCMs is presented in Annex A1.8. All the measures presume an existing fire and were classified as mitigating, rather than preventive. They are categorized as engineering, inherent or procedural in accordance with Appendix 6 of FSA guidelines.

It was agreed between experts that RCMs considered as “low hanging fruits” could be sorted out, meaning RCMs with low estimated cost and which can be recommended without further evaluation. These RCMs are listed and shortly described in Annex A1.9.

The RCMs were ranked by experts on both risk reduction potential and estimated costs. The ratings presented in Annex A1.10 summarize the results from this ranking process. Further, based on the ratings a limited number of RCMs were considered as top-ranked and are summarized in Table 21.

Table 21: Top-ranked Detection RCMs

Top-ranked RCMs	RCOs described in Section 10.2	Comments
Combined smoke and heat detection	Combined smoke and heat detection	
Fibre optic linear heat detection		New technology evaluated in WP4
Ban / closure of side (PS&SB) openings (open ro-ro spaces)	Ban / closure of side (PS&SB) openings (open ro-ro spaces)	
Increased frequency of fire patrols	Increased frequency of fire patrols	
CCTV covering all decks	CCTV covering all decks	
Thermal imaging cameras	Flame detection on weather decks	New technology evaluated in WP4
Conventional flame detection		
Detector drone or camera on rail	*Not further described*	Too low TRL
Additional detection means in AFV areas	Additional detection means in AFV areas	Requires specific AFV areas

10.2 Detailed description of relevant RCMs

This section contains a detailed description of the top-ranked risk control options identified in the pre-screening process.

10.2.1 *Combined smoke and heat detection*

Combined smoke and heat detection can be achieved in different ways, using different combinations of different technologies. This RCM focuses on the effect of this combination, rather than on specific technologies. However, for the cost-effectiveness analysis the conventional integrated point smoke and heat detector is considered. This detector is a conventional point smoke detector with an extra temperature sensor. The fibre optic linear heat detection is evaluated in a dedicated report (EMSA, 2018).

The smoke and heat detection technology used influences the response time, e.g. linear or volume detection provides better coverage than point detection with shorter response time in case of non-optimal fire locations. Furthermore, heat detectors responding on temperature rate-of-rise in addition to a fixed alarm temperature have generally better response times. However, the focus of this RCM is heat detection complementing conventional smoke detection and heat detection is generally considered as slow compared to smoke detection, which means that for most situations the response time is not affected by the heat detection technology (if alarm criteria is primarily based on detection of smoke). Heat detection has other benefits as discussed below.

The benefits of using combined smoke and heat detection is valid on all ro-ro spaces where smoke detection is considered (closed and open). Heat and smoke transport is affected a lot by high airflows and for open ro-ro spaces with large openings there could be need for other RCMs. Heat sensors are generally not affected by heat radiation but only by heat convection, which means that earlier detection than with smoke is unlikely since heat is ventilated together with the smoke.

In case current detection system use heat detection only, which is allowed according to the regulations, the RCM will imply a major improvement of response time for most situations with an added smoke detection system. This is a great side effect of the RCM and should be taken into account, however, the evaluation will focus on adding heat detection to already existing smoke detection since this will be the general case.

10.2.1.1 Benefits

Heat detection complements smoke detection with better monitoring of fire development and fire spread. Smoke detectors are saturated quite fast which means that increase of smoke and fire growth is hard to detect. In addition, smoke spreads fast and will be detected throughout the deck or in adjacent areas without personnel knowing where flames are present. With heat detection it is easier to follow both fire growth and fire spread, which reduce risk of wrong decisions and assist personnel in firefighting and localization of fire.

Heat detection is generally considered robust against e.g. dirt and dust, hence having a low false alarm rate. This could be beneficial in two aspects. Heat detection can remain activated during loading and discharging of the deck, when smoke detectors generally are deactivated due to high false alarm rate caused by exhaust fumes and stirred up dust from moving vehicles. Secondly, alarm criteria using the input from both the smoke sensor and the heat sensor can reduce number of false alarms. However, also response time may increase with such algorithms.

In addition, fire detection redundancy is improved with combined sensor technology.

10.2.1.2 Critical aspects

For monitoring of fire growth, it is important to sustain high temperatures for continuous heat detection in case of large fires. A conventional integrated point smoke and heat detector has sensitive electronics which may take damage.

As mentioned above, alarm criteria using the input from both the smoke sensor and the heat sensor may increase response time of the system.

10.2.1.3 Interdependencies of RCMs

Combined smoke and heat detection mainly affects RCMs related to user interface and addressability. For good monitoring of fire development and fire spread this RCM must be combined with smart algorithms and suitable user interface.

Also, the need for fire patrols or fire watchers may decrease in situations where smoke detection is deactivated. The system ability to deactivate smoke detection and not heat detection is important for the full potential of the RCM.

10.2.2 *Ban / closure of side (PS & SB) openings (open ro-ro spaces)*

Potentially, both open and closed ro-ro spaces have openings that could be closed. This Risk Control Measure focuses on the portside and starboard side openings of open ro-ro spaces.

For existing ships, this RCM consists in the closure of the existing permanent side (Portside and Starboard) openings as far as practicable. As concerns the newbuildings, this RCM consist in the forbidding the design of RoPax with open ro-ro spaces.

10.2.2.1 Benefits

The main benefit of fewer openings from a fire detection point of view is less airflow and to avoid strong gusts, which affect heat and smoke movement. In general, many openings result in increased response times, and in case the fire is close to an opening the fire can remain unnoticed for a long time.

If flame detectors or video detection is to be used onboard, it is likely to have better functionality with lesser openings due to less sun reflections and altering light. Permanent closure of openings also have other positive effects not directly associated with detection, e.g. slower fire development, restricted possible spread of smoke and fire, and increased probability of a successful extinction or suppression by the drencher system.

10.2.2.2 Critical aspects

Closure of openings on existing ships would imply that increased mechanical ventilation capacity is required, which could lead to a rather extensive and costly installation. That would also lead to increased fuel consumption since additional power supply is needed. If additional power is not available, it will mean installation of auxiliary engines for power supply. This is costly, technically challenging and likely to affect cargo carrying capacity.

Closure of large openings in the aft (and/or front) may have a negative impact on the cargo carrying capacity of the ship and was not retained as part of the Risk Control Measure.

As mentioned above regarding the intention with introducing open ro-ro spaces, a critical aspect would be potential loss of cargo, due to restrictions regarding e.g. carrying dangerous goods in closed ro-ro spaces. Commercially, this could also affect the customer to choose a different route/ship/company for all of its cargo and this means the ship owner does not only loose the dangerous cargo but potentially also important customers and market shares.

10.2.2.3 Interdependencies of RCMs

Permanent closure of openings directly affects RCMs related to open ro-ro spaces, e.g. reduction of strong gusts by net over openings and use of alternative fire detection systems.

Since decreased response times and higher reliability are expected for heat and smoke detection in closed ro-ro spaces, the need for increased frequency of fire patrols can be affected.

10.2.3 Increased frequency of fire patrols

The fire patrol frequency is a key parameter for fire prevention and early detection. The fire patrol can smell smoke at very early stage of fire development, see and smell fuel spills before ignition, hear the noise from malfunctioning mechanical equipment and disturb unsolicited activities.

Efficient fire patrols are required as per SOLAS II-2/7.8 and SOLAS II-2/20.4.3.1 on passenger ships carrying more than 36 passengers and specifically in special category spaces. However, it is unclear what is meant by “efficient” with regard to the frequency of fire patrols and it can have different meanings for different ships. The size of the ship for example has a large impact on the cost versus frequency of fire patrols since it may imply hiring of additional crew.

This RCO implies increasing the frequency of fire patrols from every 60 minutes to every 30 minutes.

Table 22: Probabilities of early detection failure by the fire patrol due to *too low frequency of fire patrols*

Patrol frequency	P(Early detection by the fire patrol)	P(Early detection failure by the fire patrol)
120 min	16.5%	83.5%
90 min	21.5%	78.5%
60 min (reference)	30%	70%

Another approach could have been to have more frequent fire patrols only when the fire ignition probability is the highest. For example, there could be several fire patrols e.g. every 30 minutes for the first 1,5 hour of journey and then only fire patrols every 120 minutes (for long journeys). The fire ignition probability is greater in ro-ro spaces just after leaving port since the vehicles are still warm and faults initiated while driving can develop into fire with some delay. However, this RCM implies fire patrols in ro-ro spaces every 30 minutes throughout the whole journey.

The RCM only considers increased frequency of fire patrols and not more efficient fire patrols with regard to quality. Quality aspects include equipment, communication means, accessibility, motivation, experience and training.

10.2.3.1 Benefits

If present at the fire location, fire patrols have higher potential of early detection of incipient fires or potential fires compared to automatic fire detection systems. Increased patrol frequency implies increased probability of a patrol passing a fire during the incipient phase. Further, many fires are caused due to electrical problems, which normally means overheated components or cables and a long incipient phase with smouldering fire, which sometimes produce too little smoke to be detected by the smoke detectors.

Also, fire patrols can give extra attention to known fire risks, such as refrigeration units, or to spaces without efficient fire detection system, such as weather decks and spaces close to ventilation outlets in open and closed ro-ro spaces.

10.2.3.2 Critical aspects

More scheduled fire patrols do not automatically mean that the fire patrols will take place as planned. High workload and low motivation can be reasons for skipped or shortened fire patrols. Control systems with checkpoints can be supportive.

Efficient fire patrols are dependent on both frequency of fire patrols and quality of the inspection. Quality aspects include suitable equipment, e.g. gas sniffer or IR-camera, low motivation, e.g. tired, stressed and unfocused. Further, other aspects are accessibility problems, lack of training and experience, and communication flaws.

10.2.3.3 Interdependencies of RCMs

RCMs related to the quality aspects of fire patrols will have greater impact if the frequency of fire patrols is increased. In addition, the overall efficiency of fire patrols affects all RCMs related to the efficiency of automatic fire detection systems. However, fire patrols and fire detection systems are most often complementary, and regardless of the efficiency of either technical systems or fire patrols it is also positive with redundancy.

10.2.4 *CCTV covering all decks*

To cover a complete deck, the cameras should be placed alternated on both sides of the deck and high enough to see over the cargo. A fire alarm should automatically display relevant camera at the control panel with information on drencher section. This implies that at least one camera per section is needed.

For CCTV (video surveillance) one can also use thermal imaging cameras. In general, these cameras would imply a much higher cost, but will add heat information to the image. This information is valuable for fire localization, especially in case of much smoke, and to assist firefighting. In combination with software algorithms, it is also possible to detect fires or hot spots that could potentially develop into a fire. However, restricted field of view due to cargo will limit the possibility of such detection (for all decks with limited space between cargo and deckhead).

Conventional CCTV cameras can also be used together with fire detection algorithms. Flame detection is more robust than smoke detection but face the same limitations with restricted field of view as mentioned for thermal imaging cameras. Smoke detection is more promising since smoke will spread over the cargo and can be detected by the cameras. There is sometimes still a trust issue with regard to false alarms for these systems, especially for use on open and weather decks. However, the technology is already used in enclosed spaces such as machinery rooms and might work in closed ro-ro spaces.

The RCM focuses on CCTV cameras without fire detection algorithms. However, installation of good quality cameras adds the benefit of possible future software update for automatic fire detection. Much research is focused on video detection and this technology might be considered as a good alternative for all ro-ro spaces in the near future.

10.2.4.1 Benefits

For fire detection, the main benefit of a CCTV system (without fire detection algorithms) is confirmation of fire. Due to many false alarms the fire must be confirmed before fire-fighting actions are initiated. In addition, the fire location must be confirmed before activation of the drencher system since high airflow can cause smoke detection further away from the fire and not directly above it. Normal procedure is to send a runner to the position of the fire alarm, but much time can be saved if the fire can be confirmed by CCTV. For example, if remote control of the drencher system is combined with CCTV, it could be possible for the officer in charge to quickly confirm that there is a fire and release the drencher very quickly.

Other benefits of CCTV are possible confirmation that the drencher has been activated, although it could probably be very difficult to see through the smoke, and lower risk of wrong decisions due to communication flaws between bridge and runner or other crew members. There are also benefits not related to fire, i.e. all kind of surveillance.

In case of an alarm where a camera show smoke-filled image, a recordable CCTV would allow to play back and see what caused the alarm.

10.2.4.2 Critical aspects

The field of view can be very limited due to a small space between the cargo and the deckhead. Flames can be obstructed, but smoke should be possible to confirm. However, in case of a larger fire it can be hard to locate the fire due to dense smoke.

Contamination of the camera lens or poor light conditions can affect the visibility. Also the resolution and quality of the video stream is critical for decision based on CCTV.

A recordable CCTV system is more expensive, more complicated, and requires storage capability, increasing with the number of cameras.

10.2.4.3 Interdependencies of RCMs

CCTV must be combined with good user interface and addressability for the full potential of the RCM. As mentioned above a fire alarm should automatically display relevant camera at the control panel with information on drencher section.

CCTV covering all decks could also affects the need for increased frequency of fire patrols. Depending on the quality and field of view of the cameras the fire patrol can potentially detect smoke, unauthorized charging, presence of passenger etc., by monitoring of the cameras. However, it cannot replace the fire patrol because e.g. the smell of smoke is a very good detector not possible through CCTV.

10.2.5 *Flame detection on weather decks*

For now, there are no requirements on automatic fire detection on weather decks. Any type of fire detection would therefore imply a potential huge decrease in early detection failure for weather decks. However, there is a trust issue with regard to false alarms for most available systems.

Flame detection, either conventional or by video stream analysis, is considered to be the most suitable system technology with least problems. Flame detection by thermal imaging cameras is evaluated for weather decks in another part of this study (WP4). Further description of this RCM focuses on conventional flame detectors.

Conventional flame detectors are usually constructed to detect radiation at several narrow wavelength bands to be able to distinguish a flame from other sources of radiation, e.g. hot surfaces or sunlight. Most common today are multi-spectrum IR detectors or combined IR/UV detectors. In combination with advanced algorithms, for instance analysing the flickering of the radiation, a lot of potential false alarms are prevented.

Flame detection is suitable for weather decks since the detectors can overlook large areas from a distance. Further, flame detection has been used for long time in outdoor applications, especially where liquid or gas fires are expected to occur (e.g. in the oil and gas industry). As long as the flames are within the detector’s field of view, most flame detectors activate an alarm within seconds or sometimes within milliseconds. In addition, flame detection is sometimes the only realistic alternative for outdoor applications due to difficulty of smoke and heat detection.

10.2.5.1 Benefits

The main benefit of this RCM is obvious since no automatic fire detection is currently required.

Benefits related to flame detection compared to other technologies are that one detector can cover a large area (if not obstructed) and that there is no need for heat or smoke transport to the detector. Radiation is not affected by airflow, and other weather conditions such as rain or snow will not obstruct all radiation (might require somewhat larger fire).

In addition, conventional flame detectors are very fast in case any flames are within field of view.

10.2.5.2 Critical aspects

Flame detectors must most often see the flames (reflections can sometimes be detected) and the field of view is therefore critical. High cargo, such as trucks, can significantly affect the field of view, and it is important to have high positions of the flame detectors, e.g. on the chimneys or other structures. Good detector positions are not always possible for all weather decks.

Detection by flame radiation means rather slow detection in case of smouldering fires or slow growing fires. For example, electrical fires which were identified as one of the main risk contributors in ro-ro spaces in the previous FIRESAFE study typically start as smouldering fires. Furthermore, for conventional flame detectors sun blinding can sometimes be a problem, which means that combined radiation from a fire and the sun might be interpreted as no fire.

Dirt or ice might contaminate the detector lens. However, internal heating of the window can be provided and it is fairly common with internal lens supervision, which means that a fault signal is provided if the lens is contaminated.

10.2.5.3 Interdependencies of RCMs

Flame detection on weather decks only affects (is only affected by) other RCMs related to automatic fire detection on weather decks. Manual detection, such as fire patrols, complement automatic fire detection systems as for all other ro-ro spaces.

10.2.6 *Additional detection means in AFV areas*

Additional detection means in AFV areas requires specific AFV areas, otherwise the RCM would imply additional detection means throughout all ro-ro spaces. Specific AFV areas is not yet reality due to several reasons, including information of which vehicles that are actually AFVs and high effort for sorting and loading the vehicles. In near future the number of AFVs can become more than non-AFVs making it even harder to have specific AFV areas. However, it might be possible to sort out specific AFV types if wanted, e.g. vehicles with the largest battery packs or specific gas vehicles (LNG, CNG, LPG, Hydrogen, etc.).

Additional detection means can imply a secondary fire detection system, either to improve redundancy or to achieve faster response. These include heat detection (see description on combined smoke and heat detection) and flame detection. If risks are considered higher in AFV areas it might be motivated to have more expensive fire detection solutions.

However, which has been most discussed is to provide gas detection for potential pre-warning of an AFV fire or explosion risk. Gas can possibly leak from a gas-powered vehicle and as explained and studied in the document (Federal Ministry of Transport and Digital Infrastructure, 2015), batteries tend to emit gases before they start burning. Likewise, hydrogen may escape from the tank of fuel cell vehicles.

A conventional fire detection system reinforced with a gas detection system throughout the ro-ro spaces in both closed and open ro-ro spaces was evaluated separately in this study. This solution was ranked as “very low” with regard to cost-efficiency and “medium” with regard to risk reduction and was not part of the limited number of top-ranked RCMs.

10.2.6.1 Benefits

The benefit of gas detection is to provide for potential pre-warning of an AFV fire or explosion risk. Thermal imaging cameras might as well provide pre-warning and other complementary fire detection means can improve response time or redundancy.

If specific AFV areas are realized, additional detection means can be installed locally to a relatively low cost compared to if all ro-ro spaces would be covered, assuming the number of AFVs are low.

10.2.6.2 Critical aspects

The most critical aspect is the need for specific AFV areas, which is not yet reality. Due to increasing number of AFVs compared to non-AFVs this might never be feasible.

For further evaluation of this RCM it is important to study different detection means separately.

10.2.6.3 Interdependencies of RCMs

To separate vehicles and to have specific AFV areas onboard should be evaluated in detail before further evaluation of this RCM.

In addition, there are a lot of potential interdependencies related to detection means and area of implementation, which is not yet clearly specified at this stage.

10.3 Selected RCOs

Based on the above detailed descriptions of the RCMs, their perceived cost-effectiveness, Technology Readiness Level (TRL), and availability, three risk control options were selected by the experts for further cost-effectiveness analysis:

- Combined smoke and heat detection;
- Ban / closure of side (PS&SB) openings (open ro-ro spaces); and
- Increased frequency of fire patrols.

10.4 Technical Specifications of selected RCOs

10.4.1 *Combined smoke and heat detection*

As described in section 10.2.1, combined smoke and heat detection can be achieved in different ways, using different combinations of different technologies.

The system investigated in the context of this study is a conventional integrated point smoke and heat detection system (i.e. detector is a conventional point smoke detector with an extra temperature sensor).

The same coverage as the one required for the smoke detectors in the FSS code (see Table 3: Spacing of detectors (FSS Ch. 9 Table 9.1)) is considered.

The heat detectors investigated activate at a temperature threshold value of 74°C, which is consistent with the threshold currently set for heat detectors used in ro-ro spaces and compliant with the current regulations on heat detectors (“Heat detectors shall be certified to operate before the temperature exceeds 78ºC but not until the temperature exceeds 54ºC”).

The Response Time Index (RTI) is a measure of how quickly a detector’s thermal element will respond when exposed to a gas temperature at or above its alarm threshold. The RTI of the heat detector part of the combined heat and smoke detector considered in this study is 100 ($m^{1/2}.s^{1/2}$).

10.4.2 *Ban / closure of side (PS&SB) openings (open ro-ro spaces)*

This risk control option consists in forbidding the design of RoPax with open ro-ro spaces and closing the existing side openings of the open ro-ro spaces for existing ships.

For newbuildings, the design of RoPax without open spaces shall be designed according to the regulations. No additional safety improvement is investigated in the context of this RCO.

For existing ships, the side openings shall be closed with steel plates. The “new” closed ro-ro space shall comply with the regulations applicable to closed ro-ro spaces.

In particular, these spaces will require a ventilation system, and a separation between the closed ro-ro space and the weather deck part, if applicable as well as a redefinition of the spaces and adjustments in the cargo certificate. The solution consisting of a separation through overpressure in the closed ro-ro space part and a gutter between the closed ro-ro space and the weather deck types is considered in this study.

10.4.3 *Increased frequency of fire patrols*

The fire patrols shall be conducted immediately after departure and then every 30 minutes. No change in the quality of the fire patrol is investigated.

Current fire patrol is conducted based on a pre-determined route and controlled by checkpoint tool. Fire patrol shall be dressed in long sleeved clothing preferably in non-melting material and proper shoes so that if a fire is found they are likely to act on it fast with good probability of success. Patrol carry VHF radio, flashlight, a hand held heat camera and the checkpoint pen.

10.5 Quantification of RCO effectiveness

10.5.1 *Supporting simulations – Open ro-ro spaces*

Among the 3 types of RCOs selected in FIRESAFE II, only 2 can be considered from a numerical simulation point of view. These are the closing of the openings and the implementation of heat detectors. The following section details the results.

10.5.1.1 Background

The results presented should not be considered as a pure reflection of reality. In other words, they are valid for a certain situation and a certain set of parameters. That means that if, for example another burning molecule was considered, different results could probably appear. Indeed, another molecule could produce less smoke, then the heat detectors could detect earlier than the smoke detectors.

The same could be observed with a different size of the openings, or a different cargo configuration, or a different mechanical ventilation condition, etc.

The results presented are here to describe a general trend, to support the quantification of the expected risk reduction.

10.5.1.2 Consequences of using heat detectors on the models

Compared to smoke detection, on average, heat detectors activate about 530 s later than smoke detectors (all scenarios considered). However, it should be noted that it is always the heat detector the closest to the fire that activates first.

Running simulations with heat detectors only corresponds to scenarios when the smoke detectors were deactivated or underwent a failure causing them to be ineffective.

Table 23summarises the results in terms of detection time when only heat detectors are considered. Heat detectors activate at a temperature threshold value of 74°C.

Table 23: Simulation results for the open-deck configuration with heat detectors only

Scenario				First heat detection - s	ATSFR - s	Quantity
No Wind	*Slow*	*L1*		679	797	HF
		L2		804	973	HF
		L3		859	812	HF
	Interm.	*L1*		475	532	HF
		L2		562	678	HF
		L3		631	564	HF
	Medium	*L1*		384	415	HF
		L2		454	518	HF
		L3		509	424	HF
			Wind origin			
Wind	*Slow*	*L2*	*Fore*	ND	1134	HF
			Port	ND	-	-
			Starboard	ND	964	HF
	Interm.	*L2*	*Fore*	ND	739	HF
			Port	ND	897	HF
			Starboard	ND	913	HF
	Medium	*L1*	*Fore*	ND	350	V
			Port	517	367	V
			Starboard	511	362	V
		L2	*Fore*	ND	561	HF
			Port	ND	672	HF
			Starboard	ND	690	HF
		L3	*Fore*	ND	371	HF
			Port	ND	492	HF
			Starboard	ND	482	HF

As it can be observed, heat detectors always activate when no wind condition are considered. These scenarios are representative of the vessels being at port, where smoke detectors are likely to be deactivated during the loading and unloading of cargo to avoid any false alarms.

In windy conditions (with the initial conditions considered in the study), in general there is no heat detection. This is mainly due to the fact that the wind refreshes the air in the vessel, decreasing the temperature of the hot smoke layer. Only in 2 cases, when the wind comes from the side of the ship and when the fire is located at the front of the deck (confined area), a heat detection is observed. At this location, the fire is less impacted by the wind, so as the hot layer.

In terms of early or late detection, the results of the simulations, presented in Table 24, informed that the use of heat detectors only, for scenarios without wind, leads to late detection in 8 out of 9 cases (if T[20] is equal to 2 min) and 9 cases out 9 (if T is longer than 3 min).

No early detection is observed for scenarios with wind using only heat detectors.

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[20] Constant that takes into account the different actions following the detection for safe first response, introduced in 9.2.3.

Table 24: Simulation results for the open-deck configuration in term of early vs late detection with heat detectors only

Scenario				Criteria for early detection - 0 ≤ (ATSFR-RTSFR (2min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (3min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (4min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (5min)) - s
No Wind	Slow	L1		-2	-62	-122	-182
		L2		49	-11	-71	-131
		L3		-167	-227	-287	-347
	Interm.	L1		-63	-123	-183	-243
		L2		-4	-64	-124	-184
		L3		-187	-247	-307	-367
	Medium	L1		-89	-149	-209	-269
		L2		-56	-116	-176	-236
		L3		-205	-265	-325	-385
			Wind origin				
Wind	Slow	L2	Fore	-1134	-1134	-1134	-1134
			Port	-	-	-	-
			Starboard	-964	-964	-964	-964
	Interm.	L2	Fore	-739	-739	-739	-739
			Port	-897	-897	-897	-897
			Starboard	-913	-913	-913	-913
	Medium	L1	Fore	-350	-350	-350	-350
			Port	-270	-330	-390	-450
			Starboard	-269	-329	-389	-449
		L2	Fore	-561	-561	-561	-561
			Port	-672	-672	-672	-672
			Starboard	-690	-690	-690	-690
		L3	Fore	-371	-371	-371	-371
			Port	-492	-492	-492	-492
			Starboard	-482	-482	-482	-482

10.5.1.3 Consequences of closing the openings on the models

As exposed previously, the open ro-ro space was modelled with numerous openings on the sides of the deck. As a consequence, the deck was exposed to the weather, especially wind conditions. One of the aims of this risk control option (i.e. closing the openings) is to get rid of the influence of weather conditions on the fire development. Therefore, the wind is not considered in this new set of simulations.

The second consequence of closing the opening is the need for the ro-ro space to be mechanically ventilated. Consequently, fans were modelled based on the technical specifications provided by the ship owner: 2 fans located fore of the ship, with an aperture of 2.4 m^2 each, supplying 105 000 m^3/h each. The aft part of the vessel remains open (no air mechanical air exhausts).

10.5.1.3.1 Results

Table 25 summarises the results in terms of detection time. Heat detectors activate at a temperature threshold value of 74°C.

Table 25: Simulation results for the open-deck configuration with RCOs. HF = Heat Flux, V = Visibility

Scenario			First smoke detection - s	Second smoke detection - s	First heat detection - s	ATSFR - s	Quantity
RCO (no wind - deck closed - mechanical ventilation)	*Slow*	L1	91	160	990.0	468	V
		L2	102	121	676.0	1015	HF
		L3	82	132	801.0	723	V
	Interm.	L1	76	117	690.0	488	V
		L2	79	108	481.0	672	HF
		L3	61	106	589.0	519	HF
	Medium	L1	70	110	549.0	402	HF
		L2	73	89	384.0	514	HF
		L3	49	78	475.0	387	HF

10.5.1.3.1.1 Smoke detection

A direct comparison between the no wind cases with no RCOs and the no wind cases with RCOs should be performed carefully. Indeed, the closing of the openings and the addition of mechanical ventilation change two key parameters in the fire development and the smoke dispersion. A delay of the first smoke detection up to 24 s can be observed when considering the RCOs. This can be explained by a tendency of the ventilation to dilute the smoke in the total air volume available. The same trend is observable for the second smoke detection.

10.5.1.3.1.2 ATSFR analysis

The same precaution should be taken into account when comparing directly ATSFR (no wind) to ATSFR (no wind + RCOs). For example, at the location L1, it can be observed that the ventilation has a significant influence on the smoke dispersion and dilution. That is why there are more situations where the visibility exceeds its threshold value first, before the heat flux (compared to results exposed in Table 25). However, this influence decreases as the fire is located away from the ventilation supplies.

10.5.1.3.1.3 Early/late detection

In Table 26, the same results (i.e. with RCOs) are presented in terms of early versus late detection using the concept presented in 9.2.4.3. Sensitivity to the *T* constant was studied using values ranging from 2 to 5 minutes. Positive results are obtained when the detection is considered early, the value indicates the margin. When the result is negative, the detection is considered late, the value indicating the delay.

Table 26: Simulation results for the open-deck configuration in term of early vs. late detection with RCOs. Early detection is presented in green, late detection in orange

Scenario			Criteria for early detection - 0 ≤ (ATSFR-RTSFR (2min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (3min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (4min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (5min)) - s
RCO (no wind - deck closed - mechanical ventilation)	*Slow*	L1	257	197	137	77
		L2	793	733	673	613
		L3	521	461	401	341
	Interm.	L1	292	232	172	112
		L2	473	413	353	293
		L3	338	278	218	158
	Medium	L1	212	152	92	32
		L2	321	261	201	141
		L3	218	158	98	38

In Table 26, an overall good performance of the smoke detection can be observed.

10.5.1.4 Combined RCOs – Combined Smoke and Heat detection and Closure of side (PS&SB) openings

Table 27 presents the results considering the heat detection time for the evaluation of RTSFR.

Table 27: Simulation results for the open-deck configuration in term of early vs. late detection with RCOs. Consideration of heat detection

Scenario			Criteria for early detection - 0 ≤ (ATSFR-RTSFR (2min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (3min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (4min)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (5min)) - s
RCO (no wind - deck closed - mechanical ventilation)	*Slow*	L1	-642	-702	-762	-822
		L2	219	159	99	39
		L3	-198	-258	-318	-378
	Interm.	L1	-322	-382	-442	-502
		L2	71	11	-49	-109
		L3	-190	-250	-310	-370
	Medium	L1	-267	-327	-387	-447
		L2	10	-50	-110	-170
		L3	-208	-268	-328	-388

As it can be observed, the detection with heat detectors is considered to be late in the majority of the cases considered. Even if the heat detection can allow for a more precise location of the fire, it happens in general too late for a safe first response.

10.5.2 *Supporting simulations – Closed ro-ro spaces*

10.5.2.1 Consequences of using heat detectors on the models

For the case of the closed ro-ro spaces, only one RCO where simulations can bring relevant information is applied: the use of combined heat and smoke detection as fire detection. Simulations assumptions are the same as explained previously, only the mean of detection has changed. As explained for the case of the open ro-ro spaces, the heat detectors activate at a temperature threshold value of 74°C.

The results on detection time using heat detector are presented in the Table 28.

Table 28: Simulation results for closed ro-ro space case with only heat detector

Scenarios			First heat detection - s
Fire Growth	**Position of fire**	**Ventilation**	
Slow	L3	Normal	ND
Slow	L2	Normal	ND
Slow	L1	Normal	539
Medium	L3	Normal	471
Medium	L2	Normal	425
Medium	L1	Normal	351
Fast	L3	Normal	211
Fast	L2	Normal	252
Fast	L1	Normal	291
Fast	L2	Half	209
Medium	L2	Half	376
Fast	L2	Double	270
Medium	L2	Double	477

As expected, the time of detection by heat detectors is longer than with smoke detectors (same results as the open ro-ro space). For the case of slow fire growth, the heat detection system has not been activated within the time of simulations (for the position L3 and L2). An average of the detection time delay is 350 s for the medium fire growth and 250 s for the fast fire growth.

The Table 29 presents the results from simulations about early/late detection using heat detector.

Table 29: Simulation results for closed ro-ro space case with only heat detectors

Scenarios			Criteria for early detection - 0 ≤ (ATSFR-RTSFR (2)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (3)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (4)) - s	Criteria for early detection - 0 ≤ (ATSFR-RTSFR (5)) - s
Fire Growth	**Position of Fire**	**Ventilation**				
Slow	L3	Normal	ND	ND	ND	ND
Slow	L2	Normal	ND	ND	ND	ND
Slow	L1	Normal	40	-19	-79	-139
Medium	L3	Normal	-196	-256	-316	-376
Medium	L2	Normal	-132	-192	-252	-312
Medium	L1	Normal	-43	-103	-163	-223
Fast	L3	Normal	-134	-194	-254	-314
Fast	L2	Normal	-163	-223	-283	-343
Fast	L1	Normal	-195	-255	-315	-375
Fast	L2	Half	-123	-183	-243	-303
Medium	L2	Half	-83	-143	-203	-263
Fast	L2	Double	-180	-240	-300	-360
Medium	L2	Double	-152	-212	-272	-332

As observed for the case of the open ro-ro space, the fore detection based on heat detector is considered to be late in the majority of the cases considered. Even if the heat detection can allow for a more precise location of the fire, it happens in general too late for a safe first response.

10.5.3 *Combined heat and smoke detection*

Based on the simulation results discussed in section 10.5.1, the experts estimated the risk reducing effect of the RCO Combined heat and smoke detection. A workshop gathering most of the experts listed in Annex A1.12, representing the different range of competencies, was organised to collect the experts' opinions.

The same reference vessels as in the previous steps of the FSA is taken as the basis for the quantification. Details of these vessels are provided in section 7.5.2. All the vessels are equipped with a smoke detection system (closed and open ro-ro spaces).

Experts first quantified the benefits of having a combined an additional heat detection, without taking into account the detection time. The line of reasoning are reported in the column 'Affecting factors' of Table 30. A high degree of agreement between experts was reached in the first round.

The probability of having an early detection with the heat detection system was then taking into account to obtain the risk reducing effect of the RCO. This factor was estimated to 10%. The results are presented in Table 30.

Table 30: System detection failure

RCO	*Affected nodes*	*Affecting factors*	*Closed ro-ro space*	*Open ro-ro space*
Combined heat & smoke	Internal failure - **Manual deactivation - Individual det.**	Heat detection is less likely to be deactivated during loading/unloading, hot works, etc.	9.95%	
	Internal failure - **Manual deactivation - System**	Heat detection is less likely to be deactivated during loading/unloading, hot works, etc.	9.90%	
	Internal failure - **Technical failure - Individual det.**	Assuming smoke & heat work independently Unlikely that both will be faulty at the same time	8.50%	
	Internal failure - **Technical failure - System**	Unaffected by type of detector (e.g. power failure, signal failure…)	0.00%	
	Internal failure – **Contamination / damage - Individual det.**	Contamination will not impact the heat detection. Damage will affect both heat and smoke detection. Heat detection is less sensitive for contamination, which is more likely in open ro-ro spaces.	5.00%	
	Internal failure - **Contamination / damage - System**	Not affected	0.00%	
	External cause - Poor detector pos. - **Poor location**	Not affected	0.00%	
	External cause - Poor detector pos. - **Poor spacing**	Not affected	0.00%	
	External cause - Type of fire - **Small amount of soot**	Soot is not a determining factor for heat detector	10.00%	
	External cause - Type of fire - **Too rapid fire**	Important for decision - have the information that it is a rapid fire	1.50%	
	External cause - Fire position - **Inside cargo / vehicle**	Breakage of glass [300°C] - cf. Babrauskas	0.00%	
	External cause - Fire position - **Close to vent**	[For open ro-ro space] - Fire could not detect by smoke detector because the smoke is ventilated away from the det. - it is still possible to detect with heat det.	0.20%	1.00%
	External cause - **High airflow**	Heat transport is not affected by high flow, contrary to particulates transport, especially in case of solid (detector) disturbances	10.00%	

10.5.4 *Ban / closure of side (PS&SB) openings (open ro-ro spaces)*

Two nodes of the open ro-ro space fault trees for the *Standard RoPax* are impacted by the closure of the side openings: the *Contamination / damage - Individual detection* and *Fire position - Close to openings*.

Following the implementation of the RCO, it is considered that the probability of failure of these two nodes is similar to the probability of failure for the closed ro-ro spaces. This quantification is summarized in the Table 31.

Table 31: Reduction for the nodes impacted by the RCO *Ban / Closure of side (PS&SB) openings (open ro-ro spaces)*

Node	Open ro-ro space (before implementation of the RCO)	Closed ro-ro space	Reduction
Contamination / damage - Individual detection	1.05%	0.7%	33.3%
Fire position - Close to openings	3%	1%	66.6%

10.5.5 *Increased frequency of fire patrols*

A normal compartment fire typically has four development phases: incipient phase, growth phase, fully developed and a decay phase. The incipient phase is an initial period with a small, often smouldering fire. The duration of the incipient phase depends on fuel characteristics, local air currents, ignition source location and physical arrangements. For a vehicle fire, it can vary from non-existing to hours. For example, a hydrocarbon fire has no incipient phase, upholstered furniture (such as seats etc.) often have an incipient phase of 10-40 minutes (Collier & Whiting, 2008) and electrical fires, which is one of the most common fire origins in parked vehicles (Li, 2004), can have very long incipient phases (up to hours).

If the fire patrol passes during the incipient phase of a fire, it can be assumed (A) that it will be detected and (B) that it is during this phase that detection early enough for safe manual first response is possible. Assuming (C) that the incipient phase of a vehicle fire lasts between 15 and 60 minutes (uniformly distributed), then the probability that the fire patrol passes during the incipient phase of a fire (early detection), can be calculated for varying fire patrol frequencies with the following result.

Table 32 presents the probability of early detection failure by the fire patrol because of *too low frequency* according to the frequency of the patrol.

Table 32: Probabilities of early detection failure by the fire patrol due to *too low frequency of the fire patrol*

Patrol frequency	P(Early detection by the fire patrol)	P(Early Detection Failure by the fire patrol)	Reduction
60 min (reference)	30%	70%	0%
30 min	50%	50%	28.5%

10.6 Estimation of risk reduction by the implementation of RCO

The above quantifications of the selected detection RCOs were integrated into the main fire risk model, from which effects on the total risk could be calculated. The relative risk reductions of the selected detection RCOs for each of the generic ships are presented in Figure 45 for Newbuildings and in Figure 46 for Existing ships. The results are presented in terms of relative risk reductions to standardize the impact (reduction) of the RCO on the PLL, which is different for the three generic ships for example depending on their varying passenger capacity.

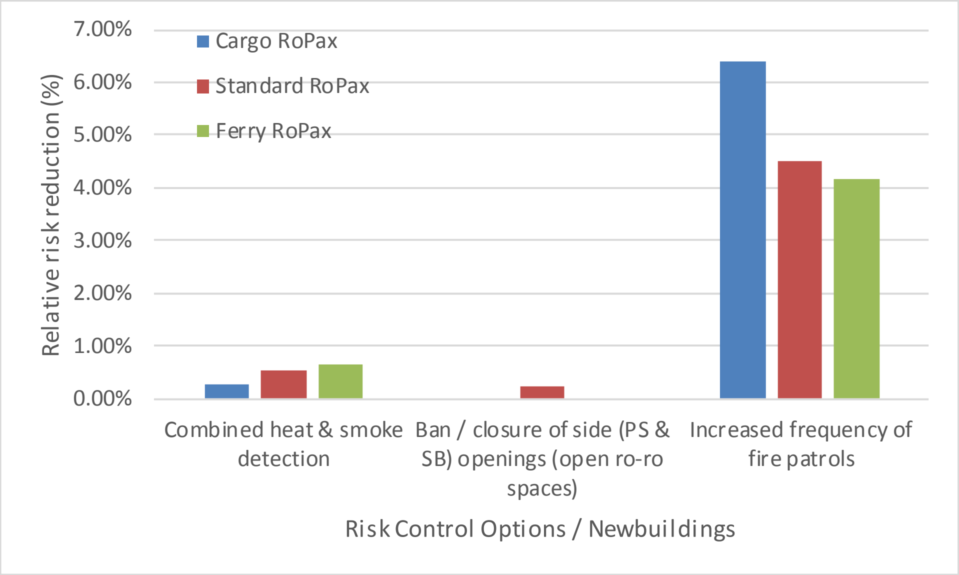

Figure 45: Relative Risk Reduction of Detection RCOs for Newbuildings

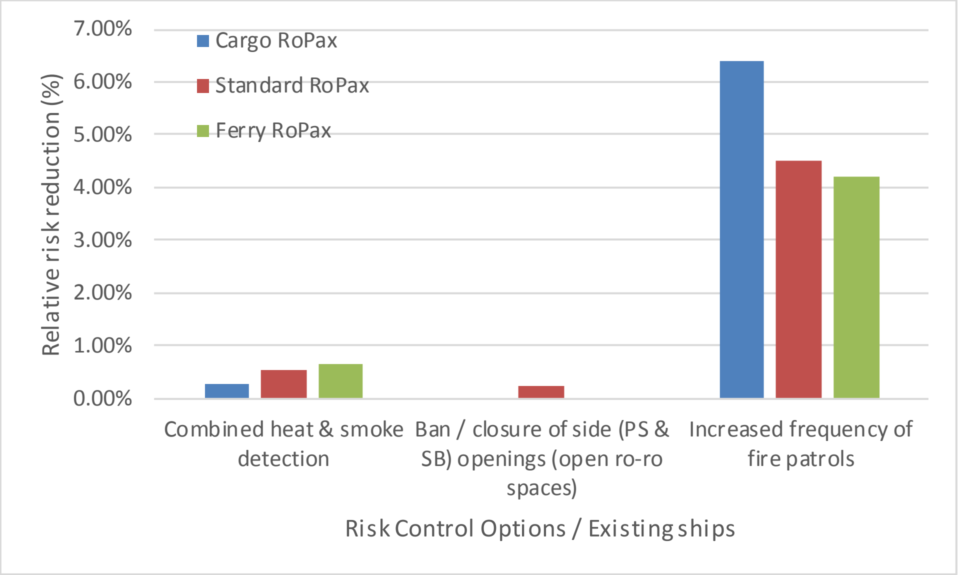

Figure 46: Relative Risk Reduction of Detection RCOs for Existing Ships

Regardless of ship category and status (i.e. Newbuildings vs. Existing ships), the RCO with the highest risk reduction potential is *Increased frequency of fire patrols*, with approximately 6.4% risk reduction on *Cargo RoPax*, 4.5% for *Standard RoPax* and 4.2% for *Ferry RoPax*. These figures apply for Newbuildings but the general results are the same for Existing ships. The differences in relative risk reductions come from the fact that *Cargo RoPax* have large weather decks (35% of the total ro-ro area for the generic *Cargo RoPax* ship) without any fixed detection system. Doubling the frequency of fire patrol dramatically increases the chance of detecting a fire that could not be detected otherwise.

The RCO *Combined heat and smoke detection* has a relative risk reduction below 1% for all ships (with the lowest efficiency for *Cargo RoPax*, due to a smaller proportion of spaces fitted with fixed detection systems compared to *Standard and Ferry RoPax*.

Finally, the RCO *Ban of side openings* only applies to *Standard RoPax*, the only ship category with open ro-ro spaces considered in the study. This RCO is ranked third in terms of efficiency with a relative risk reduction of 0.23%.

It should also be noted that the relative risk reductions presented and discussed above only take into account the effects of the respective RCOs on the Detection node in the main fire risk model event tree (and potential subsequent effects due to improved detection). However, any effects that the RCOs could have directly on the other main branches of the main fire risk model event tree (e.g. more likely containment from *Ban/Closure of openings*, or earlier decision through quicker fire localisation from *Combined heat and smoke*) were disregarded in this part of the study and were instead further studied in the Combined Assessment part of the FIRESAFE II study (EMSA, 2018).

11 RISK CONTROL OPTIONS - DECISION

Swift and effective decision-making in the case of fire detection in the ro-ro space has a profound effect on fire outcomes, making it possible to select and engage in the appropriate response with minimal delay. This decision-making is supported by sense-making on behalf of bridge and deck personnel who work together to gather information, assess the situation and build a decision base.

Risk Control Options (RCOs) for decision-making were developed following a procedure of:

- Focusing on risk areas requiring control;
- Identifying potential risk control measures (RCMs);
- Evaluating the effectiveness of the RCMs; and
- Group RCMs and select suitable RCOs for further cost-effectiveness analysis (CEA).

This procedure engaged a number of experts from human factors, classification society and the industry and led to the final selection of 3 RCOs presented in this chapter.

11.1 Identification of RCMs

In order to identify preliminary RCM candidates, the fault tree for decision-making (Figure 38 to Figure 41) was reviewed for nodes or node clusters with particularly high contributions to risk. Initially, a longer list of briefly described ideas for RCMs was created, assessed and ranked for their risk reduction potential and cost. Annex A1.10 summarizes the results from this ranking process. In the next step, a short-list of 6 RCOs was created, focussing on the areas of information integration and sensemaking on the bridge, wayfinding, localisation and accessibility on the deck, and mandate/competence for early extinguishment activation. These RCMs are summarized in Table 33.

Table 33: Top-ranked RCMs Decision-Making

RCM 01: Alarm system design & integration
RCM 02: Signage and markings for effective wayfinding and localisation
RCM 03: Technical aids for fire identification and monitoring
RCM 04: CCTV system for fire identification and monitoring
RCM 05: Spacing of cargo for accessibility
RCM 06: Organisational preconditions for early activation of drencher system

11.2 Detailed description of relevant RCMs

This section contains a detailed description of the top-ranking RCMs identified by the project group of experts.

11.2.1 *Alarm System Design & Integration*

Early decision-making in the event of a ro-ro space fire depends on clear, unambiguous information about the location, context and spread of the fire, information that should be made available through a user-friendly interface for the fire alarm and related systems. However, reviews and interviews made within FIRESAFE II have shown that alarm systems and their interfaces are often wanting both in terms of the information they offer and how this information is presented to the user. A lack of relevant and immediately accessible information can cause severe delays in decision-making allowing the fire to expand, thereby creating an even more difficult operative situation. For these reasons, an RCM for Alarm System Design & Integration was created.

RCM: To fully support fire incident decision-making, the fire alarm system interface and other panels and resources on the bridge relevant for fire-related decision-making shall be designed to provide immediate, precise and accessible information to support the localisation of a fire.

In order to fulfil these goals, systems should be designed according to a philosophy for alerting and presentation consistent for all installations on the bridge. Indications shall follow a consistent alarm presentation scheme (wording, vocabulary, colour, position). Alarms shall be immediately recognisable on the bridge and shall not be compromised by noise or poor placing. The system shall provide cues for attention through at least two senses (visual, aural). The interface shall provide alarm addressability, allow the crew to identify the alarm history and the most recent alarm. The system shall provide the means to suppress alarms while making sure that alarms with ongoing trigger conditions are still clearly visible.

For newbuildings, the fulfilment of these demands shall be demonstrated through human factors evaluation and validation e.g. human factors analysis, bridge simulation and bridge demonstration. Fulfilment shall be demonstrated using at least two approaches and shall cover key functionalities and system usability, operation under degraded alarm system functionality, the prevalence of false alarms, possible interference with other systems or activities and possible effects on workload, potential for errors and confusion.

For existing ships, opportunities arising during maintenance, revision or replacement should be taken to fulfil these demands, using expert assessment (e.g. according to usability heuristics and identified requirements) to review the replaced or revised system.

11.2.1.1 Benefits

An alarm system interface which is designed according to user needs and which is integrated with other relevant resources will maximise efficiency for information gathering and interpretation in the early stages of a fire. Use-centred design decreases the risk of misunderstandings or omissions caused by the alarm system interface, hence providing a barrier against confusion, erroneous decisions and actions that may delay fire management. Use-centred design and integration also reduces workload on the bridge, making more resources available for critical tasks. This will increase the speed of fire localisation and strengthen situation awareness in all ensuing decision-making.

11.2.1.2 Critical Aspects

For a fire alarm interface to work well in its intended context, the interface should not only be assessed in isolation. When the system is installed, there will always be a risk of conflict with other systems on the bridge competing for the crew's attention. Therefore, any system considered for the bridge should be analysed for the possibility of integrating it with other relevant systems and displays, thus creating a more harmonious workplace for bridge personnel.

11.2.1.3 Interdependencies of RCMs

Combining information about heat and smoke provides the crew with better means to assess the situation as described in 10.2.1.

11.2.2 Signage and markings for effective wayfinding and localisation

A common first response in the event of a fire alarm is to send a runner to the point of detection with the task of confirming or disconfirming the existence of a fire. Despite that demands exist for crew familiarisation, in a tightly packed ro-ro environment and given that the situation might be stressful, the runner may sometimes have difficulties in determining his or her exact location, information that is important e.g. for drencher activation and that needs to be relayed back to the bridge. Signs and markings should provide this information but may sometimes be obscured by cargo, smoke, dirt or darkness. Furthermore, their placing and design will not always have been made based on real use cases or best practice for design.

RCM: Signage and markings in the ro-ro space (e.g. for deck, sections, zones and localities) supporting wayfinding and orientation in case of fire shall be designed for easy identification and interpretation by a variety of users representing normal individual variations, e.g. in terms of height or eyesight. Signage and markings shall be adapted to typical patterns of crew movement and shall not be obstructed by cargo or fixed installations. They shall function under many different operational circumstances, such as smoke, poor lighting or different amounts and types of cargo. Signage and markings shall be brief, intuitive (make use of established vocabularies), unambiguous, legible (contrast, lettering, character height), designed using standardized symbols and shall be suitable for all relevant viewing distances and angles. These demands should be followed consistently for all relevant working areas onboard. In order to maintain their functionality, signage and markings shall be resistant to wear and tear and shall be included in a maintenance scheme.

11.2.2.1 Benefits

Providing the runner with immediate and clear information about his or her location will lower the time needed for fire localisation and confirmation and will serve to create common ground for communication between personnel on deck and on the bridge, thus creating a barrier against misunderstandings and faulty actions.

11.2.2.2 Critical Aspects

Signage and markings must be consistent with designations used in other context such as the fire alarm system interface or documentation.

11.2.2.3 Interdependencies of RCMs

It would be good practice to make sure that markings can be seen through CCTV as an extra confirmation (although the chances of this will probably deteriorate fast if there is a fire).

11.2.3 *Technical aids for fire identification and monitoring*

Localisation and monitoring of a fire will often be challenging due to the nature of the ro-ro space environment, with limited space and obstructing elements such as cargo, tarps or fixed installations. In many cases, the crew will have to resort to crude means of assessment e.g. touching of adjoining bulkheads to detect changes in temperature. Both activities of fire confirmation and continuous fire assessment would benefit from better technical support such as heat detection.

RCM: Equipment that allows for effective fire identification and monitoring shall be readily available for both patrolling and working crew. This equipment shall allow for critical tasks to be performed despite limited accessibility and visibility on deck.

11.2.3.1 Benefits

Improved means of fire localisation and assessment would increase the speed and accuracy of fire management, improving the chances of early intervention.

11.2.3.2 Critical Aspects

No critical aspects were identified.

11.2.3.3 Interdependencies of RCMs

The use of technical support for fire localisation and assessment will also be dependent on the right level of competence, both with regard to the support tools themselves and to general knowledge about fires and fire management.

11.2.4 *CCTV system for fire identification and monitoring*

The FIRESAFE II review of fire incidents onboard RoPax ships shows that where CCTV systems are available, the crew will attempt to use it for fire confirmation and assessment. Even if a CCTV system does not give a complete view of the deck, it can still give some indication of the evolving situation. Therefore, it was concluded that the use of CCTV for fire related purposes could be increased and should be given better support.

RCM: Installation of CCTV is carried out with consideration to its potential for fire confirmation and localisation, making sure that CCTV supports these activities as far as possible, providing a general overview of the deck.

11.2.4.1 Benefits

Even if CCTV will not give positive confirmation, it can give an immediate indication that a fire might be developing and will prompt the crew to raise its awareness.

11.2.4.2 Critical Aspects

A good design practice may be to introduce automatic switching to the CCTV camera closest to the triggered detector in case of a fire alarm.

11.2.4.3 Interdependencies of RCMs

No interdependencies with any other Decision related RCOs were identified.

11.2.5 *Spacing of cargo for accessibility*

Even though the minimum spacing between cargo rows and individual cargo items is regulated, it is still common that the working environment on deck is difficult with many narrow passages. In the event of fire, this will severely affect the crew’s ability for localisation, assessment and firefighting. At the same time, fixed extinguishing systems will often have limited efficiency meaning that manual firefighting is key for successful fire management.

RCM: Spacing of cargo on deck is large enough to allow access for fire localisation and assessment.

11.2.5.1 Benefits

Improved access for situation assessment and interpretation providing a better decision base.

11.2.5.2 Critical Aspects

Given that regulation already exists, there appears to be a need of other means of promoting or controlling adherence.

11.2.5.3 Interdependencies of RCOs

No interdependencies with any other Decision related RCMs were identified. However, the cargo spacing will also facilitate first response and improve the free movement of the fire patrol in the ro-ro spaces.

11.2.6 *Organisational Preconditions for Early Activation of Drencher System*

Experience shows that speedy action in the case of fire is vital to gain control, and that any delays may lead to considerably more difficult fire scenarios. This makes a strong case for early drencher activation, a practice that already exist in parts of the world fleet. However, studies within FIRESAFE II have shown that there will often be a reluctance towards drencher activation among the crew, either because of a lack of decision mandate, unfamiliarity with the drencher system and drencher room environment, or fear of any negative consequences that could be the result of faulty activation.

RCM: Early activation of the drencher system is included in fire management procedures while also ensuring that a large portion of the crew has the knowledge and mandate for drencher activation, without fear of negative consequences for the individual crew member.

To increase the likelihood of early drencher activation, the distribution of responsibilities in case of fire shall be reviewed for sufficient redundancy and a no-blame culture shall be fostered. Furthermore, decision-making at the early stages of a fire in a ro-ro space shall be explicitly included in recurring training. Training shall empower all relevant personnel to act in the case of fire and be varied to reflect different possible personnel constellations available at the time of a fire alarm, while making sure that crew actions are supported by sufficient competence and mandate.

In order to reach the full benefit of training and drills, results and observations from such activities shall be processed jointly by all participants in order to highlight lessons learned and potential areas of improvement.

11.2.6.1 Benefits

When a larger portion of the crew is empowered to act quickly (e.g. in situations where the master is not initially present on the bridge), less time being lost at the early stages of a fire incident due to insufficient decision mandate or insufficient competence. Efforts to promote uninhibited communication between officers and crew and between subgroups onboard has the potential of improving collaboration in fire incidents as well as for general operations.

11.2.6.2 Critical Aspects

Modifications with regard to decision mandate must be made with respect to the existing chain-of-command and must not run the risk of undermining decision transparency.

11.2.6.3 Interdependencies of RCMs

No interdependencies with any other Decision related RCMs were identified.

11.3 Selected RCOs

Based the perceived cost-effectiveness and feasibility of the above-described RCMs, listed in Table 33, three RCOs were ultimately selected for further cost-effectiveness analysis.

- Alarm system Design & Integration
- Improved markings/signage for way-finding and localization;
- Organisational Preconditions for Early Activation of Drencher System

11.4 Quantification of RCO effectiveness

Little data typically exists to guide the quantification of RCOs targeted at the human operator and human operative capabilities. Instead, experts within FIRESAFE II made a joint qualitative assessment of each RCO, first assessing if any further conditions were necessary for the RCO to have full effect on a particular fault tree node, then discussing the relative impact of all influencing factors.

11.4.1 *Alarm System Design & Integration*

As per the decision-making fault-tree, the properties of the fire alarm system (its interfaces and integration) will mainly affect the speed of alarm interpretation. Experience-based assessment of the nodes responsible for delays in this phase showed that they are all likely to be minimised by a well-designed and integrated system. Since the weather deck will neither have any detection system nor any fixed fire extinguishment installations whose activation would require coordination between the deck and the bridge, this RCO is only relevant for closed and open ro-ro spaces.

The node “alarm is wrongly dismissed” was left with a smaller risk reduction because of the fact that although a well-functioning fire alarm system may be installed, alarms could still be mistaken for known ongoing activities such as maintenance work or loading/unloading of cargo. The nodes for “alarm is missed”, “Time lost on information integration” and “Information misinterpreted” were all given a tenfold reduction to signify that these risks are considered minimal with the proper system support. The probability for “travel time on bridge” was reduced to zero, given that all resources necessary for fire assessment and management on the bridge are brought together in shared or adjoining interfaces. Furthermore, the Alarm System Design RCO was connected to bridge/deck communications, seeing as a well-designed and integrated system will support common ground between these environments. Communication is however also affected by both of the other selected RCOs.

11.4.2 *Signage and markings for effective wayfinding and localization*

Signage and markings represent an important resource for wayfinding and localisation in case of fire in closed and open ro-ro spaces, but seeing that manual confirmation is also affected by the cargo deck environment (tight passages, smoke, etc.), this RCO was assessed to represent a 33% reduction of probability for the “difficult environment” node. Improved signage and markings were also believed to contribute to bridge/deck communications in the way of shared vocabulary and common ground, reducing the probability of “failure of communication” by 40%. Wayfinding and localisation were deemed easier on the weather deck, which constitutes a smaller area with more cues to the person’s location. Therefore, this RCO was not believed to contribute to fire confirmation at the weather deck.

11.4.3 *Organisational Preconditions for Early Activation of Drencher System*

Working with the organization to promote early activation of extinguishing systems was believed to have a large impact on the level and distribution of competence among the crew, thus decreasing the probability of “insufficient competence” by 80%. “Poor availability of key personnel” was given a 60% reduction given that personnel may still be scarce under certain operative conditions such as during the night. Lastly, training that includes communicative practices and that covers realistic communication between the bridge and personnel on deck was believed to reduce the risk of “failure of communication” by 40%.

11.5 Estimation of risk reduction by the implementation of RCO

The above quantifications of the selected decision RCOs were integrated into the main fire risk model, from which effects on the total risk could be calculated. The relative risk reductions of the selected decision RCOs for each of the generic ships are presented in Figure 47 for Newbuildings and in Figure 48 for Existing ships. The results are presented in terms of relative risk reductions to standardize the impact (reduction) of the RCO on the PLL, which is different for the three generic ships for example depending on their varying passenger capacity.

Regardless of ship category and status (i.e. Newbuildings vs. Existing ships), the RCO with the highest risk reduction potential is *Preconditions for early activation of drencher system*, with approximately 12.0% relative risk reduction for the *Standard RoPax* and *Ferry RoPax*. This could be explained mainly by the number of areas fitted with fixed extinguishing system for the two latter ships, and the impact of the RCOs on three nodes contributing significantly to the extinguishing failure.

It should be noted that the relative risk reductions presented and discussed above only take into account the effects of the respective RCOs on the Decision node in the main fire risk model event tree (and potential subsequent effects due to improved decision). However, any effects that the RCOs could have directly on the other main branches of the main fire risk model event tree were disregarded in this part of the study and were instead further studied in the Combined Assessment part of the FIRESAFE II study (EMSA, 2018).

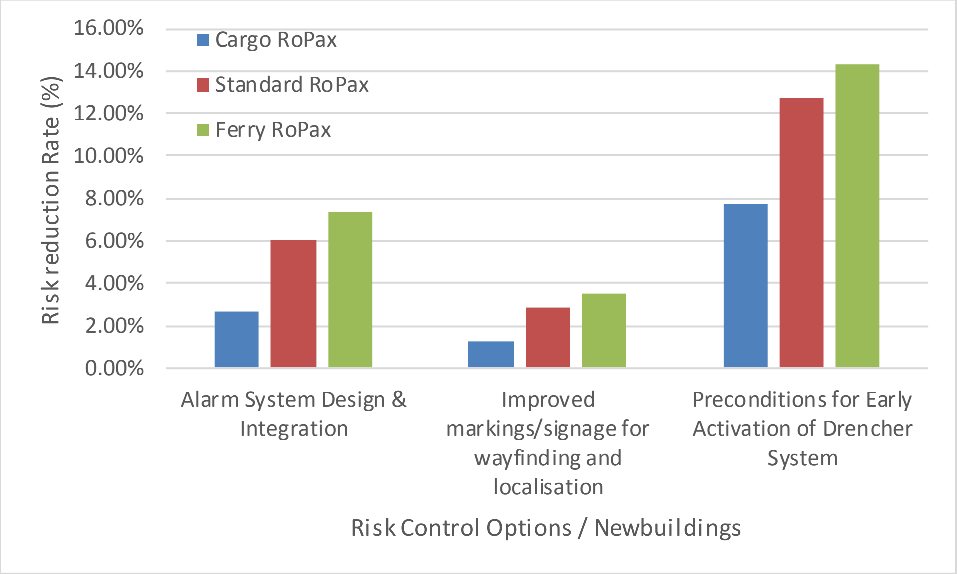

Figure 47: Relative Risk Reduction of Decision RCOs for Newbuildings

The above remarks apply for both newbuildings and existing ship. However, a higher relative risk reduction exists for RCO1 because of the probability of *time lost in information integration* being more important on existing ships.

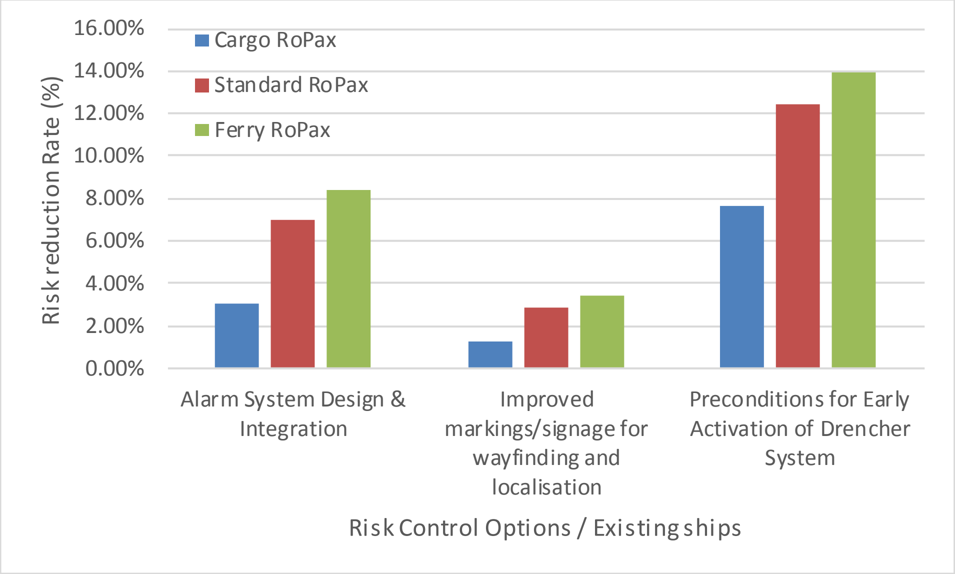

Figure 48: Relative Risk Reduction of Decision RCOs for Existing Ships

12 COST-EFFECTIVENESS ASSESSMENT

12.1 Cost-effectiveness assessment – background

12.1.1 *Cost-effectiveness measures*

As indicated in FIRESAFE (EMSA, 2016), a deep review of the risk acceptance and cost-effectiveness criteria and their comparison with those of various transport modes and industries was carried out as part of the recent EMSA 3 FSA project (Annex C of (EMSA, 2015)). Given the recentness of that study, such investigation will not be repeated in this report.

Two indices used to calculate the cost-effectiveness of risk control options are introduced in the FSA Guidelines (IMO, 2018) and have been widely used in most of the FSA studies submitted to IMO to date. These indices are the Gross Cost of Averting a Fatality (Gross CAF or GCAF) and the Net Cost of Averting a Fatality (Net CAF or NCAF).

Definitions and formulae to calculate these indices were extracted from the FSA Guidelines (IMO, 2018) and reported below:

- GCAF (Gross Cost of Averting a Fatality): A cost-effectiveness measure in terms of ratio of marginal (additional) cost of the risk control option to the reduction in risk to personnel in terms of the fatalities averted.

$$GCAF = \frac{\Delta Cost}{\Delta Risk}$$

- NCAF (Net Cost of Averting a Fatality): A cost-effectiveness measure in terms of ratio of marginal (additional) cost, accounting for the economic benefits of the risk control option to the reduction in risk to personnel in terms of the fatalities averted.

$$NCAF = \frac{\Delta Cost - \Delta EconomicBenefit}{\Delta Risk}$$

12.1.2 *Cost-effectiveness criteria*

In FIRESAFE, 6 913 600€ was selected as the CAF criterion. This value ($7.45m converted in Euro with the November 2016 exchange rate) was calculated by use of the formula based on the Life Quality Index (LQI)[21] during the GOALDS study (IMO, 2012). This criterion had been used in the FSA for ro-ro and ro-pax ships regarding the transport of electrically powered vehicles and vehicles with refrigeration units carried out in 2016 (IMO, 2016).

If updated according to the average risk free rate of return of 5%, and taking a value of preventing a fatality (VPF) of $3m in 1998 as a basis, as provided in the FSA Guidelines, the VPF in 2017 is estimated to $7.58m (6.52m€).

If updated according to the LQI formula with the GDP per capita and life expectancy at birth in 2017 from OECDstats (OECD, 2018) and portion of life spent in economic production of 0.1, the VPF in 2017 is estimated to $7.96m (6.85m€).

For consistency with the previous studies on the topic and taking into account the values updated with the above-mentioned methods, it is proposed to use 7 000 000€ as the criterion in FIRESAFE II.

12.1.3 *NCAF and GCAF*

The review of the SOLAS fire safety objectives, in particular those included in Regulations II-2/2.1.1.2 and II-2/2.1.1.3 reveals that the SOLAS Chapter II-2 objectives are not limited to the risk to life but also consider the risk of damage caused by fire to the ship, its cargo and the environment.

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[21] Formula based on the Gross Domestic Product (GDP) per capita, life expectancy at birth and portion of life spent in economic production, for OECD countries.

Therefore, in addition to the calculation of GCAF, consideration was given to the use of the NCAF criterion. This is in accordance with the approach recommended in paragraph 1.3.3 of the Appendix 7 of the FSA Guidelines (IMO, 2015) which stipulates that:

"In principle, either of the two criteria can be used. However, it is recommended to firstly consider GCAF instead of NCAF. The reason is that NCAF also takes into account economic benefits from the RCOs under consideration. This may be misused in some cases for pushing certain RCOs, by considering more economic benefits on preferred RCOs than on other RCOs.

If the cost-effectiveness of an RCO is in the range of criterion, then NCAF may be also considered."

12.1.4 *Assumptions*

The expected lifetime (T) of a RoPax ship was set to 40 years (which correspond to the life expectancy at delivery calculated in the section Analysis of the FIRESAFE II Fleet). As identified in GOALDS (IMO, 2012), "most owners will use a shorter investment period for a new ship; however, the costs are to be seen from the society's point of view. Therefore, the investment time will be equal to the ship's expected lifetime." This value was used to calculate the reduced risk in terms of fatalities averted:

($\Delta Risk = \Delta PLL * T$)

The average age of the fleet was estimated to 20 years old, this was considered in the calculation of the cost effectiveness for existing ships.

The delta cost and benefits were calculated in Net Present Value (NPV) with a discount rate of 3.5% for the period of years 1 – 30 and 3.0% for the period of years 31 – 40 (HM Treasury, 2018).

12.2 Estimation of costs – Detection RCOs

This cost identification was done in cooperation with relevant manufacturers and Stena's internal resources (conversion experts, ship's crew, ships technical superintendent, fleet managers).

12.2.1 *RCO Detection – Combined smoke and heat detection*

This Risk Control Option is applied to all ro-ro spaces currently required to have detection systems installed.

The costs of implementing this Risk Control Option were estimated for both existing ships and newbuildings.

12.2.1.1 Existing ships

Investigation of the currently installed fire detection system on the *Cargo RoPax* and the *Ferry* RoPax reveals that their respective fire detection systems can be upgraded. Therefore, the costs for the implementation of a combined smoke and heat detection system for the *Cargo RoPax* and *Ferry RoPax* were estimated based on an upgrade of the existing system. However, the *Standard RoPax* would be in need of total system renewal.

Table 34 presents the details of the costs for the implementation of the RCO Combined smoke and heat detection on existing ships.

Table 34: Details of the costs for the implementation of the RCO Combined smoke and heat detection on existing ships

Combined heat and smoke detection	***Cargo RoPax***	***Standard RoPax***	***Ferry RoPax***	**Reference**
Investment total (rounded)	**€ 145 000**	**€ 155 000**	**€ 53 000**	
Central unit / installation	€ 16 000	€ 7 752	€ 28 900	Maker
Software	€ 38 500	€ 38 500	€ 11 500	Maker
Loop units	€ 69 720	€ 68 585		Maker
Classification and commissioning costs	*€ 2 500*	*€ 20 133*	*€ 2 500*	*Maker*
Installation	*€ 8 715*	*€ 9 625*		*Maker / conversion expertise*
Yard supply	*€ 10 000*	*€ 10 000*	*€ 10 000*	*Maker*

The maintenance costs of the system are expected to be identical for both the conventional smoke detection system and the combined smoke and heat detection system. Therefore, they have not been estimated.

All the above costs presented in Table 34 are thus marginal costs. Table 35 summarises the lifetime marginal costs (in present value) for the implementation of the RCO Combined smoke and heat detection on existing ships.

Table 35: Lifetime marginal cost (in present value) for the implementation of the RCO Combined smoke and heat detection on existing ships

Combined heat and smoke detection	***Cargo RoPax***	***Standard RoPax***	***Ferry RoPax***
Delta Cost	**€ 145 000**	**€ 155 000**	**€ 53 000**

12.2.1.2 Newbuildings

As indicated above, the *Standard RoPax* represents a ship that would be in need of total fire detection system renewal. The costs of the system for a newbuilding and an existing ship are similar. It was considered by the ship owner that the costs for the *Central unit / installation*, *Software*, and *Loop units* estimated for the *Standard RoPax* and presented Table 34 (column *Standard RoPax*) are also applicable for the two other generic ships.

Although there will be some costs for the classification and commissioning, the installation and yard supply, these are expected to be identical for the installation of a conventional smoke detection system. Therefore, these costs have not been estimated accurately for newbuildings since they are not taken into account in the calculation of the marginal cost.

As for the existing ships, the maintenance costs of the system are expected to be identical for both conventional smoke detection system and combined smoke and heat detection system. Therefore, they have not been estimated.

The contacted maker indicated that the combined heat and smoke detection system is expected to be 18% more expensive than the conventional smoke detection system.

All the above leads to the lifetime cost (in present value) for the implementation of the RCO Combined smoke and heat detection on newbuildings presented in Table 36.

Table 36: Lifetime marginal cost (in present value) for the implementation of the RCO Combined smoke and heat detection on newbuildings

Combined heat and smoke detection	***Cargo RoPax***	***Standard RoPax***	***Ferry RoPax***
Delta Cost	**€ 17 500**	**€ 17 500**	**€ 17 500**

12.2.2 *RCO Detection – Ban / closure of side (PS&SB) openings (open ro-ro spaces)*

12.2.2.1 Existing ships

Closing side openings can presumably be performed during a normal docking. It is however not an easily accommodated change to ships designed with openings.

Looking at more than one ship it was understood that the cost for doing this may be very different from ship to ship. It is wise to consider the range of costs rather than just looking at one example ship.

Ventilation system is not designed to cope with an extra deck and auxiliary power may not be enough to add the requested ventilation. Assuming it is enough, the ships auxiliary engine capacity will be fully used any future additional installation such as for example scrubber installation will need additional auxiliary engine installation. Added reefer sockets may also drive cost and auxiliary power need.

Closing the side openings makes the decks defined as *closed spaces* and as per SOLAS definition. Many ships, including the vessel in question, are designed with a combined open ro-ro space and weather deck. By closing the openings i.e. making the deck defined as closed, there is a requirement in SOLAS for a separation between the now closed ro-ro space and the weather deck part, in case the operator intends to carry the same type of cargo (IMDG classes) on weather deck. This separation is not defined, and Flag States may accept different solutions. In this cost estimate, it was assumed that a separation through overpressure in the closed ro-ro space part and a gutter between the deck types would be accepted by authorities, meaning no closing device is needed for the aft.

Additional to this, the ship owner will experience loss of cargo and additional operational costs due to the closing. This is a yearly cost that was estimated for these ships and this cost will follow the ship through the remaining lifetime. Another operational issue is that the changed cargo certificate may make a ship less attractive on the route it serves. Cost for closing side openings was regarded in terms of:

- Material and closing work;
- Ventilation capacity and operating cost;
- Power availability - enough power installed (to cope with ventilation demand and electrical connections for cargo);
- Deck definition and separation; and
- Cargo situation changes.

In the context of this study, it shall be noted that the RCO permanent closure of side (PS&SB) openings would only be relevant for the *Standard RoPax*. In order to give a better understanding of the cost range for this type of RCO, two additional ships (falling in the categories *Standard RoPax* and *Cargo RoPax*) were considered.

Table 37: Details of the costs for the implementation of the RCO Ban / closure of side (PS&SB) openings (open ro-ro spaces) on existing ships

Ban / closure of side (PS&SB) openings (open ro-ro spaces)	***Standard RoPax***	***Standard RoPax (1)***	***Cargo RoPax (1)***	**Reference**
Yearly losses total*	**€ 120 000**	**€ 3 930 000**	**€ 2 040 000**	
Investment total	**€ 660 000**	**€ 13 260 000**	**€ 9 310 000**	
Added ventilation capacity	€ 500 000	€ 500 000	€ 500 000	Conversion expertise / fleet manager
*Steel and work, closing sides***	*€ 150 000*	*€ 250 000*	*€ 300 000*	*Conversion expertise / fleet manager*
Gutter	€ 10 000	€ 10 000	€ 10 000	Conversion expertise
Additional two auxiliary engines + installation		€ 2 500 000	€ 2 500 000	Conversion expertise / fleet manager
New engine room for the added aux including sub-systems		€ 2 000 000	€ 2 000 000	Conversion expertise / fleet manager
Cabling, transformer, reefer sockets, etc.		€ 1 000 000	€ 1 000 000	Conversion expertise / fleet manager
Off hire during rebuild and installation		€ 7 000 000	€ 3 000 000	Fleet manager
*Yearly losses in regard to cargo capacity **Includes material, approximately 15 tonnes of steel, and work for 30 closed openings 6 m² each				

Table 38 summarises the lifetime marginal cost (in present value) for the implementation of the RCO Ban / closure of side (PS&SB) openings (open ro-ro spaces) on existing ships.

Table 38: Lifetime marginal cost (in present value) for the implementation of the RCO Ban / closure of side (PS&SB) openings (open ro-ro spaces) on existing ships

Ban / closure of side (PS&SB) openings (open ro-ro spaces)	*Standard RoPax*	*Standard RoPax (1)*	*Cargo RoPax (1)*
Delta Cost	**€ 2 365 000 €**	**€ 69 115 000**	**€ 38 303 000**

12.2.2.1.1 *Standard RoPax* (1) (not a chosen example ship for the study) – Additional information

Included items installation: added ventilation capacity, additional power sockets for reefers, additional two auxiliary engines needed, cabling, steel and steel work approximately 30 tonnes for the openings, off hire during rebuild and installation, gutter

Included items yearly: operating fans and power sockets (auxiliary engine fuel consumption), loss of cargo due to change in cargo certificate, loss of cargo due to added installation weight (approx. 180 tonnes)

Ship owner’s comments: For this study it was assumed that it is possible to fit additional auxiliary power onboard. It shall be noted that this may not be the case in reality. This is a heavy reconstruction and it is likely to affect the cargo hold and cargo capacity of the ship even more. Regarding additional auxiliary engines it could be discussed weather to have two smaller or one bigger engine.

12.2.2.1.2 *Cargo RoPax* (1) (not a chosen example ship for the study)

Included items installation: added ventilation capacity, additional power sockets for reefers, additional two auxiliary engines needed, cabling, steel and steel work approximately 20 tonnes for the openings, off hire during rebuild and installation, gutter

Included items yearly: operating fans and power sockets (auxiliary engine fuel consumption), loss of cargo due to change in cargo certificate, loss of cargo due to added installation weight (approx. 170 tonnes)

Ship owner’s comments: For this study it was assumed that it is possible to fit additional auxiliary engines onboard. It shall be noted that this may not be the case in reality. This is a heavy reconstruction and it is likely to affect the cargo hold and cargo capacity of the ship even more. Regarding additional auxiliary engines it could be discussed whether to have two smaller or one bigger engine.

12.2.2.2 Newbuildings

For newbuildings, the “steelwork and closing sides” can be approximated to zero (even though there will be a cost for more material compared to the open design).

Yearly losses for the newbuildings is difficult to estimate and very individual.

For the *Standard RoPax*, only a major change on ship design could accommodate for the loss of cargo due to the closing of the side openings. That cost has not been evaluated and hence the figure for yearly losses is kept.

Taking into account all of the above remarks, the lifetime marginal costs (in present value) for the implementation of the RCO Ban / closure of side (PS&SB) openings (open ro-ro spaces) on newbuildings were estimated for the *Standard RoPax* and are presented in Table 39.

Table 39: Lifetime marginal cost (in present value) for the implementation of the RCO Ban / closure of side (PS&SB) openings (open ro-ro spaces) on newbuildings

Ban / closure of side (PS&SB) openings (open ro-ro spaces)	Standard RoPax
Delta Cost	**€ 3 082 000**

12.2.3 *RCO Detection – Increased frequency of fire patrols*

This RCO explores the effect of more frequent interval of fire patrol. Cost wise this could only be evaluated based on reference ship situation today. Normal patrol interval for the reference ships is 60 minutes. No cost for less frequent patrols will be given. No changes in quality are accounted for. Following was considered:

- Personnel increase;
- Possibility to accommodate additional crew; and
- Other work that will be affected by redirecting crew efforts towards fire patrolling (opportunity costs).

For the *Cargo RoPax* and the *Ferry RoPax*, one additional AB would be needed to perform fire patrols every 30 minutes. Both vessels have sufficient accommodation for one extra crew. The only cost associated to this RCO is the cost of employing one additional AB (per ship).

For the *Standard RoPax*, the investigation revealed that performing fire patrol every 30 minutes (instead of after departure and after that every 60 minutes) is feasible by rearranging the staff and task organisation. Maintenance will be affected when calling out one additional AB for more frequent patrols. The costs associated to this was estimated and are the only costs associated with this RCO.

All the above costs are presented in Table 40.

Table 40: Details of the costs for the implementation of the RCO Increased frequency of fire patrols

Increased frequency of fire patrols	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*	Reference
Yearly costs	**€ 60 000**	**€ 34 000**	**€ 60 000**	
One additional AB	€ 60 000		€ 60 000	HR department
Calling out one AB		€ 34 000		HR department

12.2.3.1 Existing ships

The implementation of this RCO does not require any initial investment but implies yearly costs throughout the lifetime of the ships. Table 41 summarises the lifetime marginal cost (in present value) for the implementation of the RCO Increased frequency of fire patrols on existing ships.

Table 41: Lifetime marginal cost (in present value) for the implementation of the RCO Increased frequency of fire patrols on existing ships

Increased frequency of fire patrols	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*
Delta Cost	**€ 853 000**	**€ 483 000**	**€ 853 000**

12.2.3.2 Newbuildings

The lifetime of a newbuilding is different than the expected remaining lifetime of an existing ship. The lifetime marginal costs are then different. These costs are presented in Table 42.

Table 42: Lifetime marginal costs (in present value) for the implementation of the RCO Increased frequency of fire patrols on newbuildings

Increased frequency of fire patrols	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*
Delta Cost	**€ 1 286 000**	**€ 729 000**	**€ 1 286 000**

12.3 Estimation of costs – Decision RCOs

12.3.1 *RCO Decision – Alarm System Design & Integration*

The fire alarm system interface and other bridge panels relevant for fire related decision-making shall be designed to provide immediate, precise and accessible information about the location of a fire. In order to clarify what the extent of required changes would be for typical ships within the reference fleet, the state of the fire alarm system was assessed for a number of ships using an interview guide (provided in Annex A1.12).

12.3.1.1 Existing ships

For existing ships, usability assessment could most likely be based on a usability heuristic employed by a human factors professional, with little need for virtual or physical demonstration. In the event that the complete fire alarm system together with presentation would have to be replaced, cost was estimated using quotes recently obtained by Stena.

Table 43 presents the details of the costs for the implementation of the RCO Alarm System Design & Integration on existing ships.

Table 43: Details of the costs for the implementation of the RCO Alarm System Design & Integration on existing ships

Alarm System Design & Integration	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*	Reference
Investment total	**€ 145 000**	**€ 155 000**	**€ 53 000**	
Replacement of the fire alarm system interface and other bridge panels	€ 145 000	€ 155 000	€ 53 000	Maker

The lifetime marginal costs for the implementation of this RCO on existing ships are presented in Table 44.

Table 44: Lifetime marginal cost (in present value) for the implementation of the Alarm System Design & Integration on existing ships

Alarm System Design & Integration	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*
Delta Cost	**€ 145 000**	**€ 155 000**	**€ 53 000**

12.3.1.2 Newbuildings

Inquiries made during cost assessment for this RCO gave that for newbuildings, additional costs would mainly be associated with time spent on verification and validation of design i.e. to check whether the design fulfils the specified demands.

This analysis would require expertise that is not likely to be present at the shipyards today, thus increasing the cost. On the other hand, it seems likely that over time, shipyards could adjust their standard bridge design (including fire alarm systems) to accommodate for usability demands, thus minimizing the need for repeated trials.

Furthermore, because of the increasing use of 3D modelling in design, methods such as virtual simulation are likely to become more available in the future, which offers more flexibility and less costly upkeep compared to physical simulators.

Details of the costs for the implementation of the RCO on newbuildings are presented in Table 45.

Table 45: Details of the costs for the implementation of the RCO Alarm System Design & Integration on newbuildings

Alarm System Design & Integration	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*	Reference
Investment total	**€ 20 000**	**€ 20 000**	**€ 20 000**	
Verification and validation of design	€ 20 000	€ 20 000	€ 20 000	HF specialist company

Table 46 summarises the lifetime marginal cost of the implementation of this RCO.

Table 46: Lifetime marginal cost (in present value) for the implementation of the Alarm System Design & Integration on existing ships

Alarm System Design & Integration	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*
Delta Cost	**€ 20 000**	**€ 20 000**	**€ 20 000**

12.3.2 *RCO Decision – Improved markings/signage for way-finding and localisation*

Costs for this RCO are deemed to be low given that updates and maintenance of signage and markings are reoccurring activities at any RoPax ship. After an initial effort e.g. to create usability guides for signage/marking usability, no further increase in cost is envisioned.

Table 47 provides the details of the costs for the implementation of the RCO Improved markings/signage for way-finding and localisation on newbuildings and existing ships.

Table 47: Details of the costs for the implementation of the RCO Improved markings/signage for way-finding and localisation on newbuildings and existing ships

Improved markings/signage for way-finding and localisation	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*	Reference
Investment total	**€ 2 850**	**€ 3 300**	**€ 3 300**	
Painting work	€ 2 450	€ 2 800	€ 2 800	Conversion expertise
Paint	€ 400	€ 500	€ 500	Maker

Table 48 presents the lifetime marginal cost associated with this RCO.

Table 48: Lifetime marginal cost (in present value) for the implementation of the RCO Improved markings/signage for way-finding and localisation on newbuildings and existing ships

Improved markings/signage for way-finding and localisation	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*
Delta Cost	**€ 2 850**	**€ 3 300**	**€ 3 300**

12.3.3 *RCO Decision – Preconditions for Early Activation of Drencher System*

This RCO is not associated with any substantial increase in cost given that administrative activities such as the updating of training schemes and written materials are already part of normal safety management.

However, lessons learned session after fire drill will result in less maintenance work.

Table 49 provides the details of the costs for the implementation of this RCO on newbuildings and existing ships.

Table 49: Details of the costs for the implementation of the RCO Preconditions for Early Activation of Drencher System on newbuildings and existing ships

Preconditions for Early Activation of Drencher System	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*	Reference
Yearly cost	**€ 10 000**	**€ 10 000**	**€ 10 000**	
Impact on maintenance work	€ 10 000	€ 10 000	€ 10 000	HR division

12.3.3.1 Existing ships

The implementation of this RCO does not require any initial investment but implies yearly costs throughout the lifetime of the ships. Table 50 summarises the lifetime marginal cost (in present value) for the implementation of the RCO Preconditions for Early Activation of Drencher System on existing ships.

Table 50: Lifetime marginal cost (in present value) for the implementation of the RCO Preconditions for Early Activation of Drencher System on existing ships

Preconditions for Early Activation of Drencher System	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*
Delta Cost	**€ 142 000**	**€ 142 000**	**€ 142 000**

12.3.3.2 Newbuildings

The lifetime of a newbuilding is different than the expected remaining lifetime of an existing ship. The lifetime marginal cost are then different. These costs are presented in Table 51.

Table 51: Lifetime marginal cost (in present value) for the implementation of the RCO Preconditions for Early Activation of Drencher System on newbuildings

Preconditions for Early Activation of Drencher System	*Cargo RoPax*	*Standard RoPax*	*Ferry RoPax*
Delta Cost	**€ 214 000**	**€ 214 000**	**€ 214 000**

12.4 GCAF / NCAF factors and RCOs ranking

Table 52 to Table 59 summarize the inputs value for the calculation of the GCAF and NCAF (as defined in 12.1.1).

The ΔRisk is difference of the potential loss of life over the expected lifetime of the vessel after and before the implementation of the RCO. The ΔCost, in present value, is the difference of the lifetime costs between reference system and the system with RCO. The ΔBenefits, in present value, is the lifetime economic benefits (reduced loss of cargo and reduced loss of ship) that follow the implementation of an RCO.

These tables also present the result of the cost benefit analysis and assessment by providing the GCAF.

The GCAF Factor is the ratio between the GCAF as calculated and the CAF criterion of €7.00M that was selected in section 12.1.2 and indicates a cost efficiency with values less or equal to 1.00.

Note that the effect of cumulative RCOs has not been assessed quantitatively and should not be performed by addition of contribution of individual RCO.

12.4.1 *Detection – Newbuildings*

Table 52 lists the input values ΔRisk and ΔCost, as well as the resulting cost effectiveness ratios GCAF, and GCAF Factors for the considered Detection RCOs on Newbuildings.

Table 52: ΔRisk, ΔCosts, GCAF and GCAF Factor values for the Detection RCOs on Newbuildings

		ΔRisk	**ΔCost**	**GCAF**			
Newbuildings	**Risk Control Options**	**Averted fat.**	**Present Value**	**GCAF**	**GCAF Factor**	**Cost effective**	**Rank**
Cargo RoPax	Combined heat & smoke detection	6.83E-04	17 500 €	25 616 574 €	3.66	No	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	1.70E-02	1 285 861 €	75 620 142 €	10.80	No	2
Standard RoPax	Combined heat & smoke detection	4.74E-03	17 500 €	3 688 474 €	0.53	Yes	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	2.09E-03	3 081 722 €	1 472 516 149 €	210.36	No	3
	Increased frequency of fire patrols	4.18E-02	728 655 €	17 448 580 €	2.49	No	2
Ferry RoPax	Combined heat & smoke detection	8.83E-03	17 500 €	1 982 318 €	0.28	Yes	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	5.89E-02	1 285 861 €	21 823 985 €	3.12	No	2

The RCO *Combined heat and smoke* was found to be the most cost-effective, on all three ship categories. In absolute terms, it proved to be cost-effective for the *Standard RoPax* and the *Ferry RoPax*, with a GCAF factor of 0.53 and 0.28 respectively. Despite identical lifetime marginal cost of the system for the three vessels (17 500€), the lower passenger capacity of the *Cargo RoPax* (186 Pax) and its higher proportion of ro-ro spaces without fixed fire detection system (33%) lessened the risk reduction effect of the RCO (6.83E-4 averted fatalities) when compared to the two other categories (4.74E-3 and 8.83E-3 averted fatalities for *Standard RoPax* and *Ferry RoPax* respectively). Hence, this RCO was not found cost-effective when implemented on the *Cargo RoPax.*

Although, the RCO *Increased fire patrols* showed the highest risk reduction efficiency (as shown in Figure 45), the high costs associated with its implementation (hiring of one additional AB over the lifetime of the ship or maintenance) makes it not cost-effective.

Finally, the RCO *Ban of side openings*, only applicable for the *Standard RoPax*, has the highest costs (due to loss of cargo capacity) and the lowest risk reduction, making it ranked third and not cost-effective.

It should be noted that the assumption taken for estimating the cost of implementing the RCO *Ban of side openings* on the *Standard RoPax* (not considered any major change on ship design to accommodate for the loss of cargo due to the closing of the side openings) is very influential on the cost effectiveness results (high recurring costs for 40years instead of a significant investment cost).

The Table 53 lists the input values ΔRisk, ΔCost, ΔBenefits and as well as the resulting cost effectiveness ratios NCAF, and NCAF Factors for the considered Detection RCOs on Newbuildings. Considering the economic benefits has no impact on the cost-effectiveness of the RCO and does not change the ranking.

Table 53: ΔRisk, ΔCosts, ΔBenefits, NCAF and NCAF Factor values for the Detection RCOs on Newbuildings

Newbuildings		ΔRisk	ΔCost	ΔBenefits	NCAF			
	Risk Control Options	Averted fat.	Present Value	Present Value	NCAF	NCAF Factor	Cost effective	Rank
Cargo RoPax	Combined heat & smoke detection	6.83E-04	17 500 €	9 999 €	10 980 666 €	1.57	No	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	1.70E-02	1 285 861 €	139 482 €	67 417 366 €	9.63	No	2
Standard RoPax	Combined heat & smoke detection	4.74E-03	17 500 €	11 061 €	1 357 198 €	0.19	Yes	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	2.09E-03	3 081 722 €	3 081 €	1 471 043 870 €	210.15	No	3
	Increased frequency of fire patrols	4.18E-02	728 655 €	92 081 €	15 243 587 €	2.18	No	2
Ferry RoPax	Combined heat & smoke detection	8.83E-03	17 500 €	12 843 €	527 560 €	0.08	Yes	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	5.89E-02	1 285 861 €	75 148 €	20 548 549 €	2.94	No	2

12.4.2 *Detection – Existing ships*

Table 54 lists the input values ΔRisk and ΔCost, as well as the resulting cost effectiveness ratios GCAF, and GCAF Factors for the considered Detection RCOs on Existing ships.

Table 54: ΔRisk, ΔCosts, GCAF and GCAF Factor values for the Detection RCOs on Existing ships

Existing ships		ΔRisk	ΔCost	GCAF			
	Risk Control Options	Averted fat.	Present Value	GCAF	GCAF Factor	Cost effective	Rank
Cargo RoPax	Combined heat & smoke detection	3.50E-04	145 000 €	414 201 833 €	59.17	No	2
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	8.54E-03	852 744 €	99 804 517 €	14.26	No	1
Standard RoPax	Combined heat & smoke detection	2.43E-03	155 000 €	63 779 278 €	9.11	No	2
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	1.07E-03	2 365 488 €	2 206 610 486 €	315.23	No	3
	Increased frequency of fire patrols	2.12E-02	483 222 €	22 818 701 €	3.26	No	1
Ferry RoPax	Combined heat & smoke detection	4.52E-03	53 000 €	11 720 551 €	1.67	No	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	3.00E-02	852 744 €	28 430 522 €	4.06	No	2

None of the RCOs investigated were found cost-effective on the existing ships. This is mainly due to the lifetime being shorter, therefore reducing the ΔRisk.

The ranking of the RCOs is changed, with the RCO *Increased frequency of fire patrols* ranking first while the RCO *Combined heat and smoke* ranked second penalized with its high initial investment cost.

The less cost effective RCO amongst the three investigated RCOs remains the *Closure of side (PS&SB) openings*.

The consideration of the economic benefits (as shown in Table 55) does not change the conclusion with regard to the cost efficiency status of the RCOs

Table 55: ΔRisk, ΔCosts, ΔBenefits, NCAF and NCAF Factor values for the Detection RCOs on Existing ships

		ΔRisk	ΔCost	ΔBenefits	NCAF			
Existing ships	**Risk Control Options**	**Averted fat.**	**Present Value**	**Present Value**	**NCAF**	**NCAF Factor**	**Cost effective**	**Rank**
Cargo RoPax	Combined heat & smoke detection	3.50E-04	145 000 €	6 794 €	394 794 727 €	56.40	No	2
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	8.54E-03	852 744 €	93 307 €	88 883 902 €	12.70	No	1
Standard RoPax	Combined heat & smoke detection	2.43E-03	155 000 €	7 514 €	60 687 365 €	8.67	No	2
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	1.07E-03	2 365 488 €	2 093 €	2 204 657 723 €	314.95	No	3
	Increased frequency of fire patrols	2.12E-02	483 222 €	61 969 €	19 892 383 €	2.84	No	1
Ferry RoPax	Combined heat & smoke detection	4.52E-03	53 000 €	8 726 €	9 790 855 €	1.40	No	1
	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Increased frequency of fire patrols	3.00E-02	852 744 €	50 871 €	26 734 481 €	3.82	No	2

12.4.3 *Decision – Newbuildings*

Table 56 lists the input values ΔRisk and ΔCost, as well as the resulting cost effectiveness ratios GCAF, and GCAF Factors for the considered Decision RCOs on Newbuildings.

With a low lifetime cost (around 3 000€), the RCO *Improved markings/signage for wayfinding and localisation* ranks first with a GCAF Factor of 0.12 for the *Cargo RoPax* and 0.02 and 0.01 for the *Standard RoPax* and *Ferry RoPax* respectively.

The second RCO is *Alarm System Design and Integration*. This RCO is also found cost effective for the three vessels considered, with a very low GCAF Factor for the *Standard RoPax* and *Ferry RoPax* and around 0.40 for the *Cargo RoPax*. Once again, this is due to the lower passenger capacity of these ships associated with a lower proportion of decks fitted with fixed detection system, making the alarm system design and integration less relevant.

The third RCO is the Preconditions for Early Action of Drencher System. For the three vessels, this RCO has the highest risk reduction. This RCO proved to be cost-effective for the *Standard RoPax* and *Ferry RoPax*, but not cost-effective for the *Cargo RoPax,* for the reasons already presented above and lack of fixed extinguishing systems on the weather deck.

Table 56: ΔRisk, ΔCosts, GCAF and GCAF Factor values for the Decision RCOs on Newbuildings

		ΔRisk	ΔCost	GCAF			
Newbuildings	**Risk Control Options**	**Averted fat.**	**Present Value**	**GCAF**	**GCAF Factor**	**Cost effective**	**Rank**
Cargo RoPax	Alarm System Design & Integration	7.07E-03	20 000 €	2 829 755 €	0.40	Yes	2
	Improved markings/signage for wayfinding and localisation	3.40E-03	2 850 €	839 332 €	0.12	Yes	1
	Preconditions for Early Activation of Drencher System	2.07E-02	214 310 €	10 338 756 €	1.48	No	3
Standard RoPax	Alarm System Design & Integration	5.63E-02	20 000 €	355 213 €	0.05	Yes	2
	Improved markings/signage for wayfinding and localisation	2.67E-02	3 300 €	123 487 €	0.02	Yes	1
	Preconditions for Early Activation of Drencher System	1.18E-01	214 310 €	1 818 952 €	0.26	Yes	3
Ferry RoPax	Alarm System Design & Integration	1.03E-01	20 000 €	193 681 €	0.03	Yes	2
	Improved markings/signage for wayfinding and localisation	4.89E-02	3 300 €	67 444 €	0.01	Yes	1
	Preconditions for Early Activation of Drencher System	2.02E-01	214 310 €	1 063 364 €	0.15	Yes	3

All the RCOs considered achieve negative NCAF, which suggest that the implementation of these RCOs can be recommended purely on economic considerations. These results are presented in Table 54. However, it should be noted that the fairly high negative NCAF achieved for the *Cargo RoPax* resulted from the relatively low risk reduction potential ΔR (the lower ΔR, the higher is the NCAF).

Table 57: ΔRisk, ΔCosts, ΔBenefits, NCAF and NCAF Factor values for the Decision RCOs on Newbuildings

		ΔRisk	ΔCost	ΔBenefits	NCAF			
Newbuildings	**Risk Control Options**	**Averted fat.**	**Present Value**	**Present Value**	**NCAF**	**NCAF Factor**	**Cost effective**	**Rank**
Cargo RoPax	Alarm System Design & Integration	7.07E-03	20 000 €	102 328 €	-11 648 412 €	-1.66	Yes	2
	Improved markings/signage for wayfinding and localisation	3.40E-03	2 850 €	49 161 €	-13 638 834 €	-1.95	Yes	1
	Preconditions for Early Activation of Drencher System	2.07E-02	214 310 €	269 363 €	-2 655 852 €	-0.38	Yes	3
Standard RoPax	Alarm System Design & Integration	5.63E-02	20 000 €	129 969 €	-1 953 124 €	-0.28	Yes	2
	Improved markings/signage for wayfinding and localisation	2.67E-02	3 300 €	61 654 €	-2 183 617 €	-0.31	Yes	1
	Preconditions for Early Activation of Drencher System	1.18E-01	214 310 €	272 012 €	-489 738 €	-0.07	Yes	3
Ferry RoPax	Alarm System Design & Integration	1.03E-01	20 000 €	150 855 €	-1 267 205 €	-0.18	Yes	2
	Improved markings/signage for wayfinding and localisation	4.89E-02	3 300 €	71 480 €	-1 393 442 €	-0.20	Yes	1
	Preconditions for Early Activation of Drencher System	2.02E-01	214 310 €	285 052 €	-351 008 €	-0.05	Yes	3

12.4.4 *Decision – Existing ships*

Table 58 lists the input values ΔRisk and ΔCost, as well as the resulting cost effectiveness ratios GCAF, and GCAF Factors for the considered Decision RCOs on Existing ships.

Most of the observations presented for the Newbuildings remains applicable for the Existing ships. However, it is to be noted that the *Alarm System and Integration* for the *Cargo RoPax* becomes not cost-effective due to the high implementation cost (need for a total system renewal).

Table 58: ΔRisk, ΔCosts, GCAF and GCAF Factor values for the Decision RCOs on Existing ships

		ΔRisk	ΔCost	GCAF			
Existing ships	**Risk Control Options**	**Averted fat.**	**Present Value**	**GCAF**	**GCAF Factor**	**Cost effective**	**Rank**
Cargo RoPax	Alarm System Design & Integration	4.13E-03	145 000 €	35 150 964 €	5.02	No	3
	Improved markings/signage for wayfinding and localisation	1.67E-03	2 850 €	1 705 299 €	0.24	Yes	1
	Preconditions for Early Activation of Drencher System	1.03E-02	142 124 €	13 849 905 €	1.98	No	2
Standard RoPax	Alarm System Design & Integration	3.28E-02	155 000 €	4 723 024 €	0.67	Yes	3
	Improved markings/signage for wayfinding and localisation	1.32E-02	3 300 €	250 758 €	0.04	Yes	1
	Preconditions for Early Activation of Drencher System	5.81E-02	142 124 €	2 444 882 €	0.35	Yes	2
Ferry RoPax	Alarm System Design & Integration	6.02E-02	53 000 €	880 729 €	0.13	Yes	2
	Improved markings/signage for wayfinding and localisation	2.41E-02	3 300 €	136 945 €	0.02	Yes	1
	Preconditions for Early Activation of Drencher System	9.94E-02	142 124 €	1 430 529 €	0.20	Yes	3

Table 59 presents the results of the cost-effectiveness assessment, taking into account the economic benefits of the risk control options. The RCOs *Improved markings/signage for wayfinding and localisation* and *Preconditions for Early Activation of Drencher System* achieve a negative NCAF for all generic ships. However, the RCO *Alarm System Design and Integration* was still found not cost-effective for the *Cargo RoPax*.

Table 59: ΔRisk, ΔCosts, ΔBenefits, NCAF and NCAF Factor values for the Decision RCOs on Existing ships

		ΔRisk	**ΔCost**	**ΔBenefits**	**NCAF**			
Existing ships	**Risk Control Options**	**Averted fat.**	**Present Value**	**Present Value**	**NCAF**	**NCAF Factor**	**Cost effective**	**Rank**
Cargo RoPax	Alarm System Design & Integration	4.13E-03	145 000 €	79 213 €	15 948 001 €	2.28	No	3
	Improved markings/signage for wayfinding and localisation	1.67E-03	2 850 €	32 093 €	-17 497 665 €	-2.50	Yes	1
	Preconditions for Early Activation of Drencher System	1.03E-02	142 124 €	176 662 €	-3 365 667 €	-0.48	Yes	2
Standard RoPax	Alarm System Design & Integration	3.28E-02	155 000 €	100 471 €	1 661 564 €	0.24	Yes	3
	Improved markings/signage for wayfinding and localisation	1.32E-02	3 300 €	40 271 €	-2 809 318 €	-0.40	Yes	1
	Preconditions for Early Activation of Drencher System	5.81E-02	142 124 €	178 010 €	-617 320 €	-0.09	Yes	2
Ferry RoPax	Alarm System Design & Integration	6.02E-02	53 000 €	116 602 €	-1 056 903 €	-0.15	Yes	2
	Improved markings/signage for wayfinding and localisation	2.41E-02	3 300 €	46 692 €	-1 800 686 €	-0.26	Yes	1
	Preconditions for Early Activation of Drencher System	9.94E-02	142 124 €	186 288 €	-444 527 €	-0.06	Yes	3

12.5 Results of the sensitivity and uncertainty analyses

A number of uncertainties were introduced while developing the risk model. As listed in (IMO, 2007), various degrees of uncertainty were associated with the following areas and factors:

- Scope and limitations: three generic ships were selected to represent the RoPax world fleet;
- Statistics: historical data are scarce and may be uncomplete;
- Outlined models: omitted branches, and not time-dependent event tree;
- The expert judgments: other set of experts may have provided slightly different estimates;
- The assumptions: yes/no probabilities; and
- Assumptions on the number of fatalities per final outcome of each event branch.

Some of the assumptions made in the risk assessment part were conservative, leading to a potential over estimation of the societal risk. As far as practicable, a high level of attention was given to explicit all assumptions used in the study with the aim to ease any potential modifications or updates of the assumptions with new data sets or different expert judgements.

Sensitivity and uncertainty analyses were performed as part of the study, where the quantifications of the risk model and in the effectiveness quantifications of RCOs were evaluated. No uncertainty was considered for the cost estimations.

Uncertainty of the estimated parameters was explicitly modelled with probability distributions for each bottom nodes of the sub risk models. Additional details on the methodology followed is provided in Annex A2. The risk assessment software @Risk (Palisade Decision Tool ©), an add-in to Microsoft Excel, was then used to perform Monte Carlo simulations (sampling of the parameters from their probability distribution) to estimate confidence intervals for the PLL and GCAF Factors.

The sensitivity analysis of the detection and decision bottom nodes concluded that for detection failure, the nodes with the largest impact were:

- Manual deactivation of the detection system;
- Low frequency of fire patrols; and
- Communication failure (between crew).

The results of the uncertainty analysis of the detection and decision RCOs is summarized in Table 60 and elaborated subsequently.

Table 60: Confidence (conf) of detection and decision RCOs having GCAF<1 based on uncertainty analysis

	Cargo				Standard				Ferry			
	New		Exist.		New		Exist.		New		Exist.	
	GCAF stat	GCAF conf	GCAF stat	GCAF conf	GCAF stat	GCAF conf	GCAF stat	GCAF conf	GCAF stat	GCAF conf	GCAF stat	GCAF conf
Detection												
Combined heat & smoke detection	3.66	1%	59.2	0%	0.53	76%	9.11	0%	0.28	92%	1.67	16%
Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	N/A	N/A	N/A	210	0%	315	0%	N/A	N/A	N/A	N/A
Increased frequency of fire patrols	10.8	0%	14.3	0%	2.49	1%	3.26	0%	3.12	0%	4.06	0%
Decision												
Alarm System Design & Integration	0.40	90%	5.02	0%	0.05	100%	0.67	65%	0.03	100%	0.13	100%
Improved markings/signage for wayfinding and localisation	0.12	100%	0.24	99%	0.02	100%	0.04	100%	0.01	100%	0.02	100%
Preconditions for Early Activation of Drencher System	1.48	11%	1.98	2%	0.26	100%	0.35	99%	0.15	100%	0.20	100%

The uncertainty analysis of the detection RCOs showed that most of the results from the static values are reliable. Analysing the RCOs with GCAF close to 1 showed that combined smoke & heat detection involves the most uncertainty, with a 78% confidence of GCAF<1 for *Standard RoPax* Newbuildings and 92% confidence for *Ferry RoPax* Newbuildings and 16% for existing *Ferry RoPax*. Hence, combined smoke & heat detection involved significant uncertainties which makes it uncertain whether this RCO will in fact be cost efficient for other RoPax ships than *Cargo RoPax*.

For the decision RCOs, the uncertainty analysis also mainly strengthened the results from the static values. The only minor deviation to be noted is that Preconditions for Early activation of Drencher System, which was cost-efficient for *Standard* and *Ferry RoPax* based on static values, has a 11% confidence of being cost-efficient also for *Cargo RoPax* Newbuildings. However, for existing ships, the corresponding confidence was only 2%.

12.6 Objective comparison of alternative options

Table 61 and Table 62 presents the GCAF factors of the detection and decision RCOs respectively.

Table 61: GCAF Factors for the different detection RCOs on each generic vessel (for both Newbuildings and Existing ships)

Detection		Newbuildings			Existing ships		
RCO #	Description	Cargo RoPax	Standard RoPax	Ferry RoPax	Cargo RoPax	Standard RoPax	Ferry RoPax
Det1	Combined heat & smoke detection	3.66	0.53	0.28	59.17	9.11	1.67
Det2	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	210.36	N/A	N/A	315.23	N/A
Det3	Increased frequency of fire patrols	10.80	2.49	3.12	14.26	3.26	4.06

Table 62: GCAF Factors for the different decision RCOs on each generic vessel (for both Newbuildings and Existing ships)

Decision		Newbuildings			Existing ships		
RCO #	Description	Cargo RoPax	Standard RoPax	Ferry RoPax	Cargo RoPax	Standard RoPax	Ferry RoPax
Dec1	Alarm System Design & Integration	0.40	0.05	0.03	5.02	0.67	0.13
Dec2	Improved markings for wayfinding and localisation	0.12	0.02	0.01	0.24	0.04	0.02
Dec3	Preconditions for Early Activation of Drencher System	1.48	0.26	0.15	1.98	0.35	0.20

The following RCOs are providing considerable risk reduction in a cost-effective manner (from low GCAF to high GCAF):

- For Newbuildings:
  - Regardless of the ship category:
    - RCO Dec2: Improved markings/signage for way-finding and localization; and
    - RCO Dec1: Alarm System Design and Integration.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System; and
    - RCO Det1: Combined heat and smoke detection.
- For Existing ships:
  - Regardless of the ship category:
    - RCO Dec2: Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec1: Alarm System Design and Integration; and
    - RCO Dec3: Preconditions for Early Activation of Drencher System.

Table 63 and Table 64 presents the relative risk reduction of the RCOs. Cost-effective RCOs are identified by the green cells.

Table 63: Relative risk reduction for the different detection RCOs on each generic vessel (for both Newbuildings and Existing ships)

Detection		Newbuildings			Existing ships		
RCO #	Description	Cargo RoPax	Standard RoPax	Ferry RoPax	Cargo RoPax	Standard RoPax	Ferry RoPax
Det1	Combined heat & smoke detection	0.26%	0.51%	0.63%	0.26%	0.52%	0.63%
Det2	Ban / closure of side (PS & SB) openings (open ro-ro spaces)	N/A	0.23%	N/A	N/A	0.23%	N/A
Det3	Increased frequency of fire patrols	6.38%	4.50%	4.18%	6.38%	4.52%	4.20%

Table 64: Relative risk reduction for the different decision RCOs on each generic vessel (for both Newbuildings and Existing ships)

Decision		Newbuildings			Existing ships		
RCO #	Description	Cargo RoPax	Standard RoPax	Ferry RoPax	Cargo RoPax	Standard RoPax	Ferry RoPax
Dec1	Alarm System Design & Integration	2.65%	6.07%	7.32%	3.08%	7.01%	8.43%
Dec2	Improved markings for wayfinding and localisation	1.27%	2.88%	3.47%	1.25%	2.81%	3.37%
Dec3	Preconditions for Early Activation of Drencher System	7.78%	12.71%	14.29%	7.67%	12.41%	13.91%

The following RCOs are providing considerable risk reduction in a cost-effective manner (from high relative risk reduction to low relative risk reduction):

- For Newbuildings:
  - Regardless of the ship category:
    - RCO Dec1: Alarm System Design and Integration; and
    - RCO Dec2 Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System; and
    - RCO Det1: Combined heat and smoke detection.
- For Existing ships:
  - Regardless of the ship category:
    - RCO Dec2: Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System; and
    - RCO Dec1: Alarm System Design and Integration.

13 RECOMMENDATION FOR DECISION-MAKING

13.1 Recommendation for decision-making

A Risk Control Option was considered cost-effective if the Gross Cost of Averting a Fatality (GCAF) is below €7 M. A Risk Control Option was also considered cost-effective if the Net Cost of Averting a Fatality (NCAF), accounting for the economic benefits of the RCO, is below €7 M.

No criteria for assessing the acceptability of the risks associated with a particular hazard (here fires in ro-ro spaces) are available to support decision-making at IMO. However, several cost-effective risk control options were identified and could be recommended to improve the safety level of the RoPax world fleet (listed below in order of risk reduction potential)[22]:

- For Newbuildings:
  - Regardless of the ship category:
    - RCO Dec1: Alarm System Design and Integration; and
    - RCO Dec2: Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System; and
    - RCO Det1: Combined heat and smoke detection.
- For Existing ships:
  - Regardless of the ship category:
    - RCO Dec2: Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System; and
    - RCO Dec1: Alarm System Design and Integration.

Some RCOs were found to have negative or low NCAF values, and as such, they should be regarded as cost-effective. However, some have GCAF values above €7 M and their potential for risk reduction may be fairly small.

The following RCOs are therefore not recommended for mandatory implementation through IMO legislation, but are highlighted as attractive alternatives for voluntary implementation by owners from a commercial point of view:

- For Newbuildings:
  - For Cargo RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System.
- For Existing ships:
  - For Cargo RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System.

The following RCOs were not found to be cost-effective and are therefore not recommended as mandatory requirements:

- For Newbuildings:
  - Regardless of the ship category:
    - RCO Det3: Increased frequency of fire patrols; and
    - RCO Det2: Ban of side (PS&SB) openings (open ro-ro spaces).
  - For Cargo RoPax:
    - RCO Det1: Combined heat and smoke detection.
- For Existing ships:
  - Regardless of the ship category:
    - RCO Det1: Combined heat and smoke detection;

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[22] As a general guidance, when several RCOs are cost-effective, the risk control options selection process should focus on preventive rather than mitigating measures, design rather than procedural measures, and should consider the risk reduction potential and the GCAF ranking, along with the uncertainty.

- RCO Det3: Increased frequency of fire patrols; and
- RCO Det2: Ban of side (PS&SB) openings (open ro-ro spaces).

It should be noted that the assumption taken for estimating the cost of implementing the RCO *Ban of side openings* on the *Standard RoPax* (not considered any major change on ship design to accommodate for the loss of cargo due to the closing of the side openings) is very influential on the cost effectiveness results (high recurring costs for 40years instead of a significant investment cost). It is recommended to further investigate this RCO considering a reconstruction of the ships layout or adding of safety systems to allow for “no cargo loss”.

Some RCOs are already (voluntarily or mandatory) implemented by some ship owners, operating their ships above minimum SOLAS requirements. Such actions are encouraged, regardless of the cost-effectiveness reported above. The results of the cost-effectiveness assessment reported in FIRESAFE II are believed to be representative for the world fleet, but they may be impacted by the intrinsic safety culture and specific procedures of the specific ship operators.

Although not studied as a particular RCO, the findings of the simulations and the risk assessment part indicated that a fire detection system in ro-ro spaces based on heat detection only (considering conventional point heat detectors) should not be allowed.

It should be noted that the risk reduction provided by each RCO was estimated with the assumption that none of the other RCOs were implemented (i.e. each RCO was assessed independently).

It should also be noted that the relative risk reductions presented and discussed above only take into account the effects of the RCOs on the respective Detection and Decision nodes in the main fire risk model. However, any effects that the RCOs could have directly on the other main branches of the main fire risk model event tree were disregarded, which may influence the cost-effectiveness of the RCOs.

These considerations were taken into account in the Combined Assessment part of the FIRESAFE II study (EMSA, 2018).

13.2 Discussion on how recommendations could be implemented by decision-makers

13.2.1 *Background*

In view of the above results, amendments to IMO regulations are discussed for the implementation of the Risk Control Options that proved to be cost-effective.

13.2.1.1 Graphic codes

Amendment proposals are presented with the convention used in IMO documents i.e.:

- Deletions are stroke through: ~~Example~~
- Additions are shown on a grey background: Example

13.2.1.2 Retroactivity

The amendment proposals detailed in the section below would, as amendments of SOLAS or FSS Code, be applicable only to ships built after their date of entry into force. In case it is decided to make these requirements also applicable to existing ships, the following requirement should be added in SOLAS II-2/1.2

2.9 Ships constructed before XXX* shall comply with regulations 20.4.1, 20.2.2.4, 20.4.3.1, 20.4.4 and 20.6.1.6 not later than the first renewal survey on or after YYY*

*XXX Date of entry into force of the amendments for newbuildings

YYY Date by which existing ships would have to comply with the new requirements. Delay may be needed, especially if it is considered to close any opening on the side.

Note: The requirements to be included in FSS Code are not covered by this proposal, and indeed, it is not deemed really practical to ask for retroactive application of the requirements given in 13.2.2.2.3. Should they need to be considered retroactive too, it could be proposed to include the following paragraph in FSS Code Chapter 1, after existing 1.3:

> 1.4 Ro-ro passenger ships the keels of which were laid or which were at a similar stage of construction before XXX shall comply shall comply with requirements 9.2.5.1.2 & 9.2.5.1.3 not later than the first renewal survey on or after YYY

13.2.2 *Combined Heat & Smoke detection*

This RCO was extensively discussed in sections 10.2.1 and 10.4.1.The intent of this RCO is to ensure that both heat elevation and smoke would trigger fire detection. RCO assessment was carried out considering conventional combined heat and smoke detectors.

13.2.2.1 Amendment proposal

It is proposed to amend SOLAS II-2/20.4.1 as follows:

> Except as provided in paragraph 4.3.1, there shall be provided a fixed fire detection and fire alarm system complying with the requirements of the Fire Safety Systems Code, so as to provide smoke and heat detection throughout vehicle, special category and ro-ro spaces. The fixed fire detection system shall be capable of rapidly detecting the onset of fire. The ~~type of detectors and their~~ spacing of the detectors and their location shall be to the satisfaction of the Administration, taking into account the effects of ventilation and other relevant factors. […]

This wording and requirement location are in line with those used in SOLAS II-2/75.2 to require smoke detectors in the accommodation, service spaces and control stations of passenger ships.

It is to be noted that, with the proposed wording, combined heat and smoke detection would be required on both passenger and cargo ro-ro ships. In case it is decided to apply such requirement to passenger ships only, the following wording could be considered:

> Except as provided in paragraph 4.3.1, there shall be provided a fixed fire detection and fire alarm system complying with the requirements of the Fire Safety Systems Code. On passenger ships, the fixed fire detection and fire alarm system shall provide smoke and heat detection throughout vehicle, special category and ro-ro spaces; on cargo ships, the type of detectors shall be to the satisfaction of the Administration. The fixed fire detection system shall be capable of rapidly detecting the onset of fire. The ~~type of detectors and their~~ spacing of the detectors and their location shall be to the satisfaction of the Administration, taking into account the effects of ventilation and other relevant factors. […]

13.2.2.2 Relevant interpretations & consequential amendments

Two key interpretations are associated with SOLAS II-2/20.4.1: IACS UI SC73 and an interpretation included in IMO MSC/Circ.1120.

13.2.2.2.1 IACS UI SC73: Fire protection of weather decks

IACS UI SC73 states:

> The requirements for a fixed fire extinguishing system, fire detection, foam applicators and portable extinguishers need not apply to weather decks used for the carriage of vehicle with fuel in their tanks.

This interpretation would remain valid and relevant with the proposed amendment.

13.2.2.2.2 MSC.1/Circ.1120: Arrangements for disconnecting detector sections during loading and unloading

With respect to SOLAS II-2/20.4.1, IMO MSC/Circ.1120 clarifies that smoke detectors may be temporarily disconnected for e.g. loading/unloading sequences. The following amendment is proposed in order to clarify that heat detectors should not be disconnected under such circumstances. Indeed, one of the identified gains of having combined heat and smoke detection is to improve detection during loading/unloading sequences.

> The smoke detector sections in vehicle, special category, and ro-ro spaces may be provided with an arrangement, (e.g. a timer) for disconnecting detector sections during loading and unloading of vehicles to avoid "false" alarms. The time of disconnection should be adapted to the time of loading/unloading. The central unit should indicate whether the detector sections are disconnected or not.
>
> However, manual call points and heat detectors should not be capable of being disconnected by the arrangements referred to above.

13.2.2.2.3 FSS Code Ch.9 §2.1.1

FSS Code Ch 9 §2.1.1 allows for temporary disconnection of the fire detection and fire alarm system. Similar to above, the following amendment is proposed in order to clarify that only smoke detectors may be disconnected:

> 2.1.1 Any required fixed fire detection and fire alarm system with manually operated call points shall be capable of immediate operation at all times (this does not require a backup control panel). Notwithstanding this, particular spaces may be disconnected, for example, workshops during hot work and smoke detectors in ro-ro spaces during on and off-loading. The means for disconnecting the detectors shall be designed to automatically restore the system to normal surveillance after a predetermined time that is appropriate for the operation in question. The space shall be manned or provided with a fire patrol when detectors required by regulation are disconnected.
>
> Detectors in all other spaces shall remain operational. In ro-ro spaces, heat detectors shall remain operational during on and off-loading.

13.2.3 *Alarm system design and integration*

This RCO was extensively discussed in section 11.2.1.The purpose of this RCO is to improve the design of the fixed fire detection and fire alarm system in order to support fire incident decision-making and ensure quick activation of the fire suppression system.

13.2.3.1 Amendment proposal

It is proposed to insert the following requirements in FSS Code Chapter 9, after existing §2.5.1.1, and the next requirements should be re-numbered accordingly:

> 2.5.1.2. [In ro-ro passenger ships,] indications shall follow a consistent alarm presentation scheme (wording, vocabulary, colour, position). Alarms shall be immediately recognisable on the bridge and shall not be compromised by noise or poor placing.
>
> 2.5.1.3. [In ro-ro passenger ships,] the interface shall provide alarm addressability, allow the crew to identify the alarm history and the most recent alarm. The system shall provide the means to suppress alarms while making sure that alarms with ongoing trigger conditions are still clearly visible.

Note 1: The wording [In ro-ro passenger ships] in inserted into brackets because the present study is focused on ro-ro passenger ships. However, the above requirements are simple, non-expensive safety measures and it seems relevant to apply them for all newbuildings

13.2.4 *Signage and markings for effective wayfinding and localisation*

This RCO was extensively discussed in section 11.2.2.

13.2.4.1 Amendment proposal

It is proposed to add the following requirement in SOLAS II-2/20.6:

> 6.1.6. In passenger ships, closed vehicles and ro-ro spaces and special category spaces, where fixed pressure water-spraying systems are fitted shall be provided with suitable signage and marking on deck and on the vertical boundaries allowing easy identification of the sections of the fixed fire-extinguishing system. Signage and markings shall be adapted to typical patterns of crew movement and shall not be obstructed by cargo or fixed installations. Section number signs shall be of photoluminescent material tested in accordance with the Fire Safety System Code. The section numbering indicated inside the space shall be same as section valve identification and section ID at the safety centre or continuously manned control station.

It was deemed relevant to include such requirement directly in SOLAS rather than in the MSC Circulars and Resolutions covering the fixed fire extinguishing systems for ease of reference, because such marking is likely to be provided by yards and not by system designers.

The proposed wording for photoluminescent signage is in line with that found in SOLAS II-2/13.3.2.5.1 for photoluminescent signs for safety signage.

14 CONCLUSION

The main objective of FIRESAFE II was to improve the fire safety of ro-ro passenger ships by cost-efficient safety measures reducing the risk of ro-ro space fires, with an aim to discuss specific proposals for rule making. In Part 1 of the study, reported here, the objective was to identify a range of risk control options (RCOs) and assess the ones most likely to be cost efficient in relation to fire detection as well as to the decision to activate the fire-extinguishing system, considering open ro-ro spaces, closed ro-ro spaces as well as weather decks, for both newbuildings and existing ships.

The risk assessment and cost-effectiveness parts of this study were developed and quantified through investigation of available failure data, fire simulations, and in case none of the previous options were available, qualitative considerations and expert judgement. Therefore, although this study is believed to be based on the best available techniques and estimates, the results presented in this study should be considered carefully bearing in mind the inherent limitations of the modelling and data availability.

The results are considered to be meaningful and to represent the best estimates to date, considering the data available. Furthermore, as far as practicable, a high level of attention was given to explicit all assumptions used in the study with the aim to ease any potential modifications or updates of the assumptions with new data sets or different expert judgements.

Some of the assumptions made in the risk assessment part were conservative, leading to a potential over estimation of the societal risk. Although the consequence part of the main fire risk model was developed to be representative to the average consequences of accidents, it should be noted that a single accident leading to a high number of fatalities within a limited period in time may skew the estimated historical societal risk. This may create a difference between the estimated historical societal risk and the risk estimated with the risk model. An over-estimation of the societal risk will generally increase the risk reduction potential of RCOs.

The costs estimated in this study were based on the estimates provided by a single ship operator. Although all efforts were put to make this study applicable for the world fleet, the cost estimates are necessarily influenced by the geographical area considered and the inherent safety culture of the ship operator involved, which already implements some of the risk control options recommended in this study on a voluntarily basis.

Quantifying the effect of all of the above assumptions and their cross-effects with a high level of precision is not realistic and some of the various assumptions might skew the overall results. However, the sensitivity and uncertainty analysis performed in the context of this study allowed, to some extent, consideration to these effects and should be considered along with the best estimate for decision making. The results of this study were considered robust enough to lead to recommendations for decision making.

The results of this study can be summarized as follows:

To consider the diverse world fleet of RoPax ships in the study, three generic categories ships were defined based on a lane metre to passenger capacity ratio:

- *Ferry RoPax*, represent RoPax ships or ferries with focus on carriage of passengers but which can also carry cargo similar to a *Standard RoPax*. These ships typically only have closed ro-ro spaces or mainly closed ro-ro spaces and a small weather deck;
- *Standard RoPax*, represent the RoPax ships with focus on both carriage of cargo and of passengers. These vessels typically have each of the three types of ro-ro spaces: closed ro-ro spaces, open ro-ro spaces and weather decks. The size of the weather deck/s is generally medium to large within this category; and
- *Cargo RoPax*, represent RoPax ships with focus on carriage of cargo and basically have a passenger capacity just enough to carry the number of drivers necessary to load the ro-ro spaces with accompanied trailers. These vessels typically have closed ro-ro spaces and large weather deck/s.

Based on the data available, the 15-year average accident frequency was estimated to 5.28E-03 fires in ro-ro spaces per shipyear and the associated historical Potential Loss of Life (PLL) to 1.50E-01 fatalities from fires in ro-ro spaces per shipyear.

In the absence of agreed definition for an early fire detection, a new concept for determining the detection was introduced. This concept is believed to be not only applicable to fire in ro-ro spaces and could be used in other FSAs focusing on fire risk. The proposed criterion compares the *Required Time for Safe First Response* (which is the time to detect the fire by automatic or manual means as well as the time necessary to set up all the appropriate first response actions following detection) to the *Available Time for Safe First Response* (the time available until conditions become untenable around the fire, disallowing first response).

Dedicated fault trees were developed focusing on the main hazards identified during the HazId. The trees were quantified to gain an understanding of the impacts on risks and to investigate in further detail the important causes and initiating events of the accident scenarios identified. This allowed quantification of the contributing detection failures as well as to calculate the overall detection failure rate. In order to consider the different types of ro-ro spaces, different trees were developed and quantified by investigation of available failure data, fire simulations and expert judgement, in case none of the previous options were available. A similar exercise was performed for Decision fault tree.

The main fire risk model developed in FIRESAFE was updated in consideration of the new findings for the Detection and Decision nodes. The societal risk due to fires in ro-ro spaces was calculated for the three ship categories. For Newbuildings, the PLL were estimated as follows: *Cargo RoPax:* 6.66E-03 fatalities per shipyear, *Standard RoPax:* 2.32E-02 fatalities per shipyear, *Ferry RoPax* 3.53E-02 fatalities per shipyear. Only a slight difference of about 1% (increase in PLL) was observed for Existing ships, mainly due to the fact that the only difference considered in this study is the non-addressability of the detection on Existing ships.

A wide range of Risk Control Measures (RCMs) were initially identified. Some of these RCMs were considered as “low hanging fruit”, meaning RCMs with low estimated cost that do not necessitate further evaluation and which can be recommended as voluntary measures to reduce the risk. Out of the remaining ones, 15 of them were identified as most promising and as potentially practicable by the experts (9 related to Detection and 6 related to Decision). These were thoroughly described and their benefits, critical aspects and interdependencies were discussed.

Out of the 9 detection risk control measures, three risk control options were selected for further quantitative cost-effectiveness analysis:

- Combined smoke and heat detection: A review of the regulations and common practices showed that smoke detection is often the only means for fire detection used in ro-ro spaces. However, the review of previous accidents and the HazId showed that heat detection could provide a way to detect some types of fire earlier and an alternative way of detecting a fire when smoke detectors are deactivated during loading and discharging of the decks. Combined point heat and smoke detectors were investigated to replace conventional smoke detectors;
- Ban / closure of side (PS & SB) openings (open ro-ro spaces): Heat and smoke movements are affected by the airflow and hence by the gusts coming from the side openings. This results in increased detection times, and in case the fire is close to an opening it can remain unnoticed for a long time. Closing the side openings of open ro-ro spaces was investigated for existing ships and the ban of open ro-ro spaces was considered for newbuildings; and
- Increased frequency of fire patrols: Many fires are caused due to electrical problems, which often means overheated components or cables and a long incipient phase with smouldering fire. These may produce too little smoke to be detected by the smoke detectors. However if passing through the space, fire patrols are more likely to give early detection of incipient fires compared to automatic fire detection systems. An increased frequency of fire patrols would imply an increased probability of a patrol passing the fire during the incipient phase and thus a higher probability of early detection. A half-hour interval between fire patrols was investigated in this study.

Out of the 6 decision risk control measures, three risk control options were selected for further quantitative cost-effectiveness analysis:

- Alarm System Design & Integration: Reviews and interviews made within FIRESAFE II have shown that alarm systems and their interfaces are often lacking both in terms of the information they offer and how this information is presented to the user. A lack of relevant and immediately accessible information can cause severe delays in decision-making, allowing the fire to expand, thereby creating an even more difficult operative situation. This RCO considers an alarm system that fully supports fire incident decision-making, as well as other resources on the bridge relevant for fire-related decision-making designed to provide immediate, precise and accessible information to support the localisation of a fire;

- Improved markings/signage for way-finding and localization: A common response in the event of a fire alarm is to send a runner to the point of detection with the task of confirming or disconfirming the existence of a fire. Crew familiarization plays a part in this task, as well as the tightly packed ro-ro space environment. Furthermore, given that the situation might be stressful, runners may sometimes have difficulties in determining their exact location, which is important information to the bridge e.g. for drencher activation. This RCO investigates the impact of improved signage and markings in the ro-ro space supporting wayfinding and orientation in case of fire. They shall be designed for easy identification and interpretation by a variety of users representing normal individual variations; and
- Preconditions for Early Activation of Drencher System: Studies within FIRESAFE II have shown that there will often be a reluctance towards drencher activation among the crew, either because of a lack of decision mandate, unfamiliarity with the drencher system and drencher room environment, or fear of any negative consequences that could be the result of faulty activation. This RCO consists in the inclusion of the early activation of the drencher system in fire management procedures while also ensuring that a large portion of the crew has the knowledge and mandate for drencher activation, without fear of negative consequences for the individual crewmember.

Costs for the implementation of these RCOs were estimated. Technical items available on the market were as far as possible quantified by system supplier offers. In addition, cost estimations were based on existing costs for material from ship operator's internal projects, specifications, reconstructions etc. The main component systems of each RCO were identified and respective costs were estimated. For any operational RCOs manning and training costs were used based on ship operator's experience. Other cost items affecting for example operations were included in the quantification when necessary.

The cost-effectiveness criteria were updated. A Risk Control Option was considered cost-effective if the Gross Cost of Averting a Fatality (GCAF) is below €7 M. A Risk Control Option was also considered cost-effective if the Net Cost of Averting a Fatality (NCAF), accounting for the economic benefits of the RCO, is below €7 M.

The FSA demonstrated that the following RCOs achieved the highest risk reduction in a cost-effective manner:

- For Newbuildings:
  - Regardless of the ship category:
    - RCO Dec1: Alarm System Design and Integration; and
    - RCO Dec2: Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System; and
    - RCO Det1: Combined heat and smoke detection.
- For Existing ships:
  - Regardless of the ship category:
    - RCO Dec2: Improved markings/signage for way-finding and localization.
  - For Standard RoPax and Ferry RoPax:
    - RCO Dec3: Preconditions for Early Activation of Drencher System; and
    - RCO Dec1: Alarm System Design and Integration.

It should be noted that the relative risk reductions of the RCOs only take into account the effects of the RCOs on the respective Detection and Decision nodes in the main fire risk model. However, any effects that the RCOs could have directly on the other main branches of the main fire risk model event tree were disregarded which may render cost-effective some RCO that were not in this part. These considerations were taken into account in the Combined Assessment part of the FIRESAFE II study (EMSA, 2018).

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A1 ANNEXES:

A1.1 Results of the Detection HazId

The resulting tabulation of fire detection hazards and risk control measures is documented below. In the fourth column (*), a notation was made for the type of ro-ro space considered, namely open ro-ro space (O), closed ro-ro space (C) or weather deck (W).

System (why?)	**Desired functions**	**Affecting conditions**	*	**Failure mode**	**Effect**	**Potential safety measures**	**Comments**
Fixed smoke/heat	Quick	Type of detector	C/O	Fire close to ventilation outlet/inlet or close to openings, causing smoke and heat to be ventilated away or to be ventilated to other detectors. Detectors close to ventilation outlet/inlet/opening can give the same potential failure.	Imprecise and delayed detection, delayed/no response or response to wrong location	* CCTV. * Heat detection (thermal imaging camera, fibre optic detection). * Flame detection, at least by openings and inlets/outlets. * Closure of openings (by wind reducing net or by permanent closure). * Reduction of openings - how much is needed? * Standardized tests and/or simulations for evaluating detection with consideration to (standardized) windy conditions. * Smoke detection in ventilation outlet. * Detection in outlet ducts. * Net on opening reducing air flow during windy conditions.	CCTV in combination with IR cameras can provide for quick detection, which is one of the major challenges.
Why: Fire awareness	Precise	Type of smoke/fire	C/O	Running diesel generators	False alarms (alarm but no fire, quite common in open ro-ro spaces on some ships)	* Procedure for when to allow passengers in ro-ro spaces (starting engines will imply risk of false alarms). * Procedure to reject cargo that cannot be connected or to not allow to run on diesel generator (only on closed ro-ro spaces), and routine to turn off running generators. * Carry enough cables to avoid units running on diesel generators.	Difficult to reject diesel heaters on trucks (remote controls) False alarms can lead to slow response, silencing of the alarm without response etc. There can be a large variety in the sensitivity of detectors, which means that some give a lot of false alarms while other ones don't.
	Reliable (No false alarm)	Ventilation/ Weather conditions	C/O	Cable failure	Faulty alarms	* Maintenance and exchange of old cables * Wireless connection	

	Robust (low maintenance, reliable for the context)	Installation design	C/O	Design/installation failure (with regard to the location of detectors, too large spacing, (no) consideration to openings, ventilation, smoke movement, etc.)	Delayed/No alarm	* Presence of fire safety engineer during installation/design * Fire simulations for the design * Competence on smoke movement incorporated in the design or during installation - required competence for company	
	System should not add complexity or require significant focus for current understanding (logic)	Alarm panel design	All	Dirt/Salt/Exhaust fumes clogging the detectors	Delayed/False/Faulty /No Alarm	* Maintenance * Filter (sock) on detectors * Better/more robust detection system, not affected dirt/clogging	The "sock" filter doesn't give any faulty alarm when the filter is clogged, however when chamber is clogging it generally triggers a faulty alarm.
	Pre-warning	At sea/ in port / work on deck	All	Illogic alarm panel layout design, address function/alarm presentation not being logical/existing or too coarse division, also due to re-builds of ships and merging/extensions of the old system, several systems, old ships with un-supported illogical systems	Delayed / Faulty response (wrong location), difficult orientation	* Fresh start in the design of the alarm systems for inherently safe systems (test, elements of design, aspects of design, design guidelines describing needs for the user=function based) * Intuitive design * Update of detection and alarm system. * Tools for quick orientation (maps and manuals). * Re-programming of the sensor addresses to make them more logical. * Addressable system telling the temperature, smoke density and heat spread on a GA or a particular frame. * Increased fire patrols. * Faster first response (training). * Ship familiarization. * Consider effect on end users in change of design * Reprogramming or update and replacement of old system.	The door to the alarm panel silences all alarms on some ships. The systems on some ships direct 4 cameras towards the point of alarm, which is a quick and much liked system. Some systems are addressable by just showing a code for the activated detector. This may be just a case of reprogramming the detector codes into more logic names, e.g. based on deck and frame number. "

	Confirmation of the fire	Address function	C/O	Button/timer to de-activate detection during loading/unloading - detection system deactivated and no one present on deck	No alarm	* Sectioning of the detection system de-activation, allowing de-activation of sections instead of the system as a whole. * Automatic activation of detection system when main engine is started or similar. * Only de-activation of smoke detectors/possibility to not deactivate heat detection. * Keeping flame detectors always activated. * A good mixture of detectors! * Possibility to disconnect each deck or even individual detectors.	Generally deactivation 10-15 minutes before arrival, when passengers are allowed on the decks, with presence of crew members. Reactivation of the detection system needs to be automatic according to regulations. Requirements nowadays are that de-activation of detection is only allowed for 30 or 15 mins (?) but many ships have significantly longer timers (e.g. 2 hours). Generally managed in cargo control room or on bridge. Is de-activation of detectors needed? -Some ships don't have them.
	Assessment/ monitoring of the fire	Environment/ Exhaust fumes	All	No-one on bridge to attend to alarm, e.g. common during loading and discharging	No response	* Routine that ME crew attends to alarms during bridge absence	
		Amount of false alarms	C/O	Failure of pre-warning of potential AFV fire	Uncontrolled/unexpected fire Late detection	* Gas detection (pre-warning). * Planned loading of AFVs. * Additional detection where AFVs are located (designated area). * Mapping of AFVs on the decks.	Increase of AFVs in the future, segregating different types of cars is complicated, Detection of an AFV fire is generally not different from detecting a conventional fire but since the consequences are potentially greater there is an increased need for pre-fire warning if possible, e.g. detection of gas leakage.
	Should not require significant workload, e.g. maintenance for proper function	Load configuration	C/O	Cable routing leading to deterioration of cables for other detectors/sections during initial fire	No possibility to follow the fire (mostly for heat detectors)	* Double loop detector signal wiring.	Generally turned off 10-15 minutes before arrivals, passengers allowed on the decks, with presence of crew members Manual connection needs to be automatic. Safe return to port requirements specify double wire routing etc.

		Fire location	All	Alcohol and other type of fire without smoke	No Alarm	Use of suitable detection system (IR-flame?)	
		Fire developing in vehicle	C/O	Damaged detectors due to high cargo	No alarm/faulty alarm	* Carry enough spare detectors	
		Type of cargo	W	Difficult to detect a fire due to no detection system or monitoring	No detection	* Flame detectors. * CCTV. * Watchmen. * To design ships with the bridge in the aft, in order to be able to visually see a fire in front.	Could be relevant for open enders to not have detection system if they are easily over viewable and watched by crew/bridge
			C/O	Confusion regarding the detection section, drencher section and CCTV numbering/section	Response in wrong location, activation of wrong drencher section, delayed response/extinguishment	* Correlation of different sections and numbering	
			C/O	False alarms	Delayed/no response	* Carry enough spares. * Procedure for when to allow passengers in ro-ro spaces (starting engines will imply risk of alarms). * At least a yearly service from the manufacturer.	

System (why?)	**Desired functions**	**Affecting conditions**	*****	**Failure mode**	**Effect**	**Potential safety measures**	**Comments**
Fire patrol	Quick detection	Training of crew (in particular fire patrol)	All	Frequency of patrols, too few	Delayed/no detection	* Dog patrols * More frequent patrols * Fire patrols at hazardous cargo more often (e.g. twice in one round).	Regulations are vague and require "efficient" fire patrols Some ships have one AB on constant fire patrol and other ships have 2 or more. The frequency of fire patrols generally vary between every 30 mins to every 2 hrs but can be much more seldom. How are fire patrols affected by shift changes, routines for runners, etc. Generally no fire patrol on open-enders (?)
Why: Fire awareness	Precise detection	Ship familiarization	All	Fire patrol focusing only on checking boxes, workload/stress causing unfocused patrol	Delayed/no detection	* Training * Motivation, hide a price * Awareness of what could happen	Likely no fire patrols on double enders, but perhaps not necessary

Fire confirmation	Quick response	Experience	All	Impossibility to detect due to too much cargo, not possible to see the fire, to get between the cargo and detect the fire	No detection	* Drone * Detector/camera on rail in deckhead or on floor * Dog patrol/screening of deck * Separation (60 cm) on cargo every X metres	Separation is a regulation requirement, but it is not/extremely seldom well applied
Fire localization	Communication	Access, (keys) for accessing the entire vessel etc.	C/O	No communication/poor communication, no radio coverage	Delayed reporting	* Designated radio for ABs * More fixed relay stations (95% coverage required according to DNV-GL F-AMC). * More fixed communication stations at ingress points or phones on deck. * Hand-held telephones connecting to the ship phone system. * Other secondary means of communication * Some kind of secondary means of communication (should also be included in training). * Key personnel should carry means of communication at all times.	Radio coverage problems particularly occur when the ship is fully loaded, hence coverage should be tested when the ships is fully loaded!
	Identification of fire/fuel	Loading condition	C/O	Disorientation	Uncertain/vague information	* Section markings, painting the frame# and drencher zones on the ship sides. * Signs * Ship familiarization * Improved training and fire drills	There is always ship familiarization for new people but the familiarization procedure varies in the fleet, it is not followed up and could be good to repeat.
	Fire confirmation	Workload, other duties	All	Insufficient equipment	NO/delayed detection	* Heat detectors * Gas sniffers * Fire patrols equipped with a first response set (e.g. SMALL BA set, gloves…). * Hand held IR camera to see fire without flames (smouldering fire, methanol fire...) * Adapt portable extinguishers to the vehicles in the area, e.g. DG or vehicles with large batteries, fuel-cells, methanol etc. * Well-dressed AB (boiler suits and shoes?, overall?). * Training for AB to know what not to wear when on duty - and why!	Correct outfit (worn clothes), equipment and training all contribute to personnel confidence to perform correct actions in case of fire and increased fire safety awareness.
	Fire assessment	Physical condition of patroller	All	Impossibility to detect early/give pre-fire warning of AFVs	NO/delayed detection	* IR-cameras * Heat detectors * Gas sniffers	

	Safe response	Possibilities of communication (radio functionality, other means, etc.)	All	Poor accessibility to all doors to/from decks	Skipped areas no/delayed detection	* Requirement that fire patrols have access to all decks	
	Localization	Location of the person upon alarm	All	Poor physical condition of fire patrols	Delayed (or no) detection	* Requirements for fire patrols - important that person is fit for purpose	
	Identification of adjacent cargo burning	Availability of equipment	C/O	Too frequent false alarms (often due to running diesel generators)	No/delayed detection/confirmation	* Better and more effective detectors.	One of the most common false alarms is because of "showers" in accommodation. To reduce the time until response it could be relevant to assembly of fire squad as soon as you get an alarm (at least from spaces with few false alarms, such as some ro-ro spaces). It could be difficult to arrange that all ABs are the same nationality.
		Management system (how often patrols are made)	All	Changing of personnel, different nationalities and communication		* Frequent and useful training, addressing communication and familiarization challenges. * Keeping the ABs or at least those on fire patrol the same nationality/language. * Debriefing after incident training. * Bulletins of learned lessons.	
		Fire drills	All	Difficult to see what type of fire it is (electrical, battery, DG, pool fire, new energy carriers), due to e.g. small separation of cargo, difficulties to access, large amount of smoke or heat, no signage of cargo/vehicles	No/insufficient assessment of fire	* It should/must be possible to keep the walk-ways clear (in particular on old vessels without raised walkways). * CCTV system could be used to back-track where the fire started. * Re-design of ships with for example ventilation trunks or other structure or equipment very close to or protruding into the cargo lane to make flush main frames (for example ventilation trunks on some ships). * Requirements for minimum separation of cargo (or apply current requirements)	In ro-ro spaces there should not be any obstacles along the ship side/anything sticking out, such as ventilation trunks - this ends up in compromised walkways. SOLAS II-2/13.5.1: "[…] Such spaces shall be provided with designated walkways to the means of escape with a breadth of at least 600mm. The parking arrangements for the vehicles shall maintain the walkways clear at all time."

		Accessibility on cargo deck	All	In-efficiency or un-safe response	Delayed response, injuries, accelerating fire	* Two-person response.	
			All	Long time until arrival on address of detection	Delayed/no confirmation	* Keeping first responders/runners in duties close to ro-ro spaces (e.g. AB).	
		Size of the vessel					

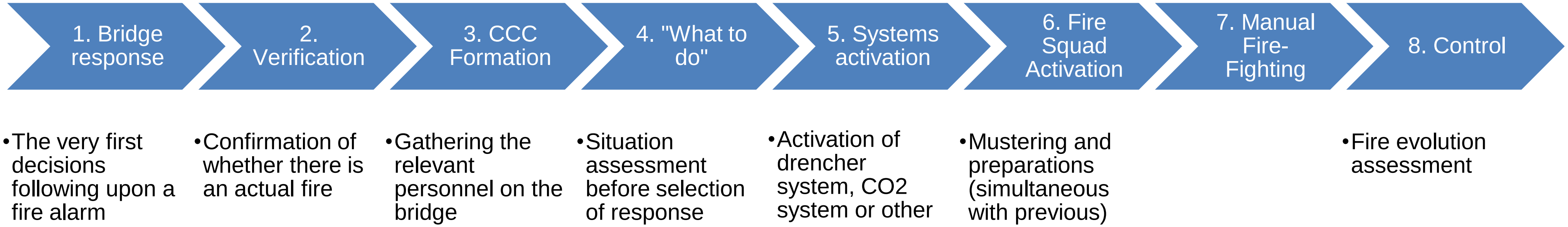
System (why?)	**Desired functions**	**Affecting conditions**	*****	**Failure mode**	**Effect**	**Potential safety measures**	**Comments**
Call point	Addressable/ precise detection	Accessibility	All	Pressed by accident, due to close to door or drunk person	False alarm	* Positioning of call point in a way which is not easily mistaken	Call point needs to be close to a door, but this could give high potential for false alarm unless the design is smart/well thought out
Why: Fire awareness	Easily understandable	Frequent in position	All	Failure to use call point due to fear (culture on board, no instruction, passenger caused the fire and want to solve the problem without causing further problems, language barrier, different culture)	No/delayed alarm	* Instructions, improved information, signs clarifying to press the button as soon as there is a small fire, symbols * Improved safety culture	Knowledge that call points are generally not connected to general alarm but that it results in a runner on site could reduce fear of pressing the button. Generally there is 2 minutes to mute the alarm before an alarm sounds only in crew accommodation, services spaces etc.. It could be good with feedback upon activation, both for crew to confirm the activated call point and for the person who pressed the button as a kind of mental response. After 2mins, it is not the GA which is sounded but
	Well-marked/ accessible	Markings	All	Illogical alarm panel, not easily understandable	No/delayed alarm and response	>>>	*See fixed smoke/heat detection system above!*
	Not false alarm pressed by accident	Colour of call point	All	No sounding alarm due to open hatch for alarm panel	No alarm	* Time-limited deactivation	

System (why?)	**Desired functions**	**Affecting conditions**	*	**Failure mode**	**Effect**	**Potential safety measures**	**Comments**
Non-dedicated CCTV	Detection		All	Poor coverage of decks due to loading conditions, number of cameras and possible positions	No possibility to CCTV for detection	* Use of CCTV, attaining full coverage * Railing system with camera/IR-detector sweeping at deckhead or on floor * Cameras creating a birds eye vision of the deck (as on some modern cars)	CCTV are required for hull integrity and generally only cover hull openings/ramps SOLAS II-1/17.1.3: "Television surveillance and a water leakage detection system shall be arranged to provide an indication to the navigation bridge and to the engine control station of any leakage through inner and outer bow doors, stern doors or any other shell doors which could lead to flooding of special category spaces or ro-ro spaces."
Why: Fire awareness	Confirmation		All	Light conditions (dark, reflections, sun)	No possibility to CCTV for detection	* Lights * Night vision * Well thought out positioning of the detectors	
	Localisation		All	Dirt, dust, soot (difficult to keep it clean)	Unclear vision	* Wipers and flush with water	
	IR		All	Damaged CCTV - malfunction	No detection by CCTV	* Maintenance	
	Assessment		C/O	Confusion regarding the detection section, drencher section and CCTV numbering/section	Response in wrong location, activation of wrong drencher section, delayed response/extinguishment	* Correlation of different sections and numbering * Clearly marked drencher zones, if possible in picture	
	Connection to detection system		All	Outdated CCTV, poor resolution/quality of images	No possibility to CCTV for detection		
	Switching to the right CCTV		All	No one attending to/viewing the CCTV monitors who could achieve detection	No detection by CCTV	* Continuously logging upon alarm. * Video surveillance - software analysis.	
			W	Placement of cameras, no deckhead or high/overlooking location	Bad coverage	* CCTV on poles	

System (why?)	Desired functions	Affecting conditions	*	Failure mode	Effect	Potential safety measures	Comments
Pass/crew by Radio *Why: Fire awareness*			All	Fire detected but no reporting/alarm due to life saving activity, response to fire instead of/before alarm, ignorance, panic.	No/delayed alarm	* Training (of crew members) * Well designed instructions and guides to passengers * Placement of call points by extinguishers	If responding to extinguishment instead of/before alarm there is a possibility that the person gets hurt, which also results in no alarm.
			All	Not reporting due to fear of blaming (caused the fire and trying to extinguish)	No/delayed alarm	*See above!*	
			All	No reporting of address or report of wrong address due to witness not knowing where he/she is, or due to running away from the fire and not knowing where the fire was	Delayed response	* Signs and markings * Smartphone application for fire detection/localisation	Double enders are generally easier to overview, have more eyes on deck No fire patrols on open enders (?)

A1.2 Data from Decision-Making HazId

The HazId workshop for Decision-Making was structured according to a timeline with phases for decision-making. The timeline was initially calibrated by the participants, in the end containing the following phases:



1. Bridge response
   - The very first decisions following upon a fire alarm
2. Verification
   - Confirmation of whether there is an actual fire
3. CCC Formation
   - Gathering the relevant personnel on the bridge
4. "What to do"
   - Situation assessment before selection of response
5. Systems activation
   - Activation of drencher system, CO2 system or other
6. Fire Squad Activation
   - Mustering and preparations (simultaneous with previous)
7. Manual Fire-Fighting
8. Control
   - Fire evolution assessment

The table below shows the results of the HazId workshop for Decision-Making. During the workshop it was decided that most efforts would go into describing decision-making activities leading up to manual interventions. Due to time constraints every item in the list was not equally developed. Instead, the interests and assessments of the participating experts were used to guide the focus of the workshop.

Phase No.	Actor	Decision	Preconditions	Hazards	Measures	Comments
1	Officer on watch	Send a runner	Depends on the form of alarm, addressability of the alarm, amount of alarms Some passenger ships have two Abs on watch, one on the bridge and one on patrol The runner could be on a fire round	It will sometimes be difficult to interpret the alarm code, where the alarm is coming from (in new systems, all alarms should be addressable) Condition of the runner (rising mean age of crew) Motivation of runner (in the light of false alarms) Lack of training/experience, doesn't know the fastest way to the alarm spot	Familiarisation	If there is an alarm reported from a weather deck, then you have somebody at the spot, and this might affect decision-making. The information from a call-point
2	Master	Role appointment	Number of staff, knowledge/experience of staff (e.g. should the officer-on-watch concentrate on navigation, or could somebody else do this)	Lack of training - training to fulfil requirements and training for actual action are different things. The training programme for seafarers is very comprehensive, more should not be added, but instead improving the quality Drills - this is up to the chief's imagination, what to do (in the future, more focus on drencher activation)		
2	Officer on watch	Check CCTV for verification	If available	CCTV could be a good resource for situation awareness and shortening response time, but it is not wide-spread		

				Power-saving lights could obstruct view		
1-6	Master	Activate extinguishing system	If not considered to be a false alarm Sensitive cargo			Most operators would wait for the master to make the decision. At Stena, several persons could make this decision and pull the drencher.
2	AB on watch	Life-saving activities				
2	AB on watch	Report back to bridge	Radio, otherwise run to phone or bridge Important input about the location of the fire, because smoke may be deceiving	No confirmation that the runner is at the right spot View blocked by cargo Well-ventilated area so that smoke cannot be sensed		
	AB on watch	Extinguish the fire				There may be a possibility for direct extinguishment prohibiting the need for further actions.
2	Crew member	Decrease damage		Lack of training - a person could hurt him/herself if they don't know how to do it		
3	Officer on watch/Master	Pull internal alarm		Hard to find the crew, you have to use telephone/radio. It takes time to call up each person if that is required. Sometimes you have to go out and find the person.		
3	Master	Assemble control team on bridge	Muster list There is a system for redundant functions Decision support Training to carry out	It takes at least five minutes from the engine room to the bridge on some *Ferry RoPax*.		

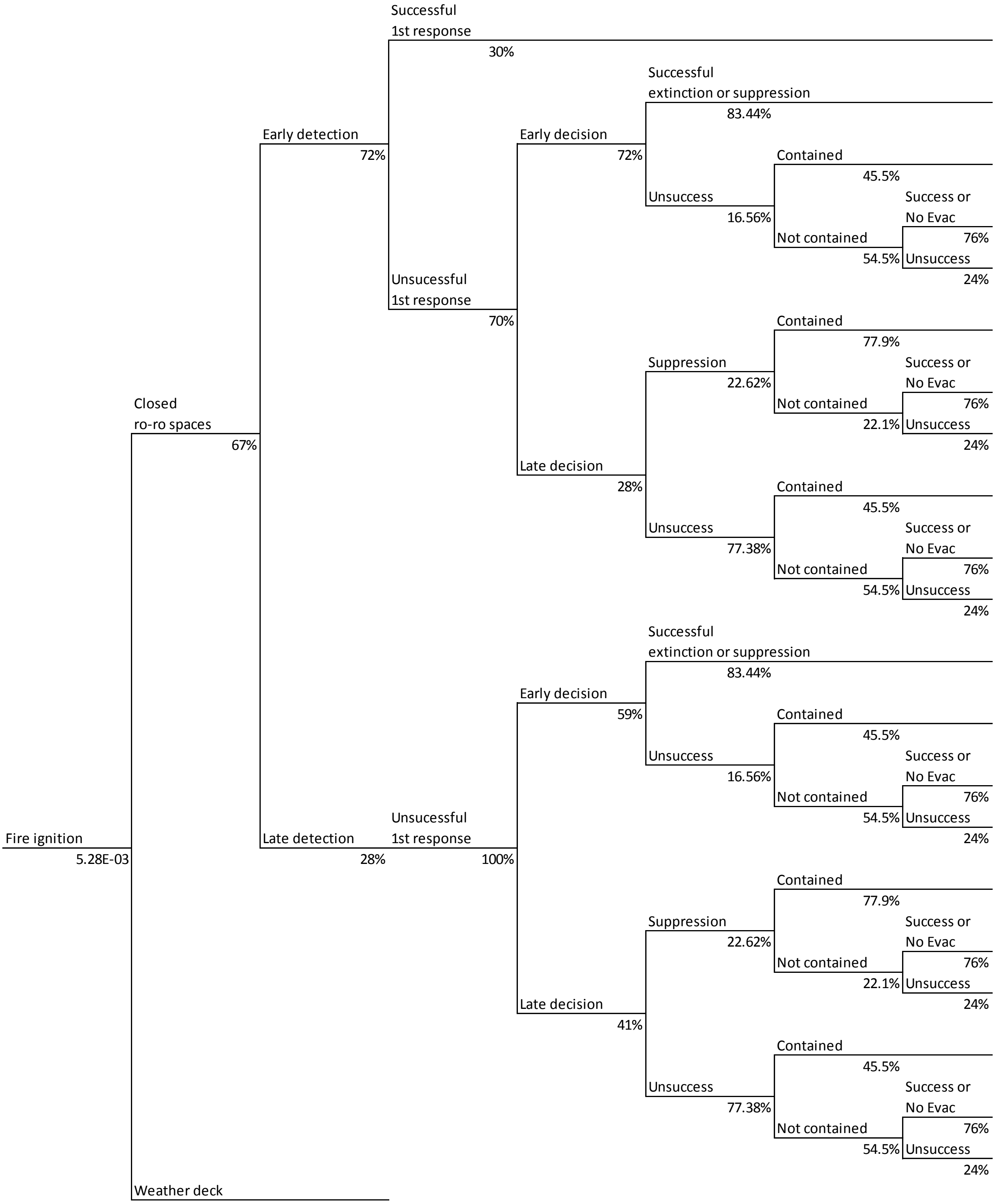
			activities on the decision support list			
4		(Activation of extinguishing system)	If a CO2 system is used then you have to make sure that no people are present			
4	Master	Activate general alarm	Depends on fire scenario	False alarms. It takes a lot of manpower to handle the passengers, they could be in the way, people could run to collect their belongings in cars etc.		
4	Master, officer on watch	Fire squad assembly				The decision process is different between Scandinavian ships and international operations, in terms of dialogue
4	Master, officer on watch	Assembly / Evacuate passengers				
4	Master, officer on watch	Inform other vessels in the vicinity				
4	Master, officer on watch	Report to JRCC				
4	Master, officer on watch	Call 112				
4	Master	Navigation e.g. to direct smoke (to avoid black-out, ensure that you can abandon ship in a safe way, avoid smoke in accommodation inlets				

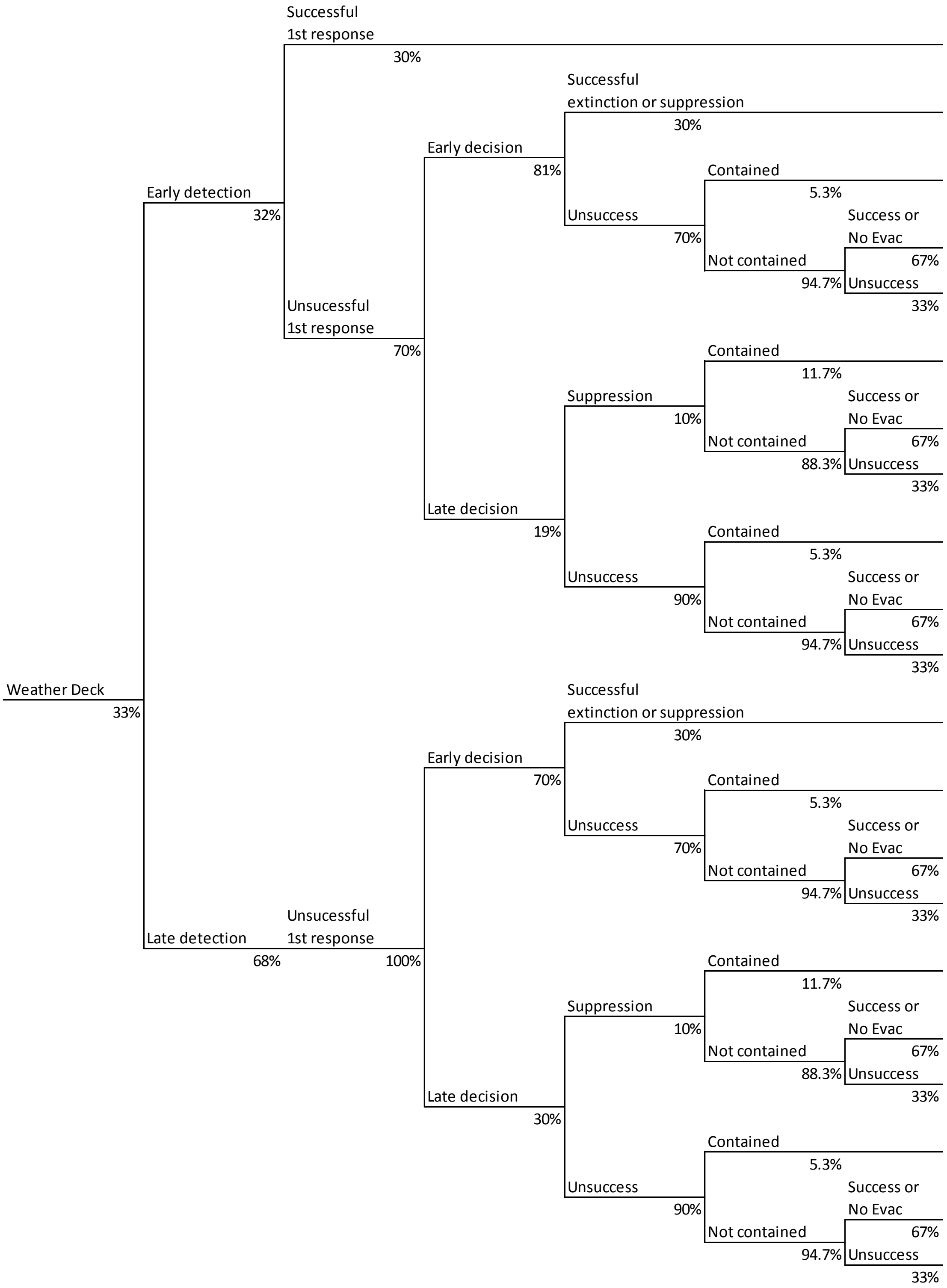
4	Master	close fire dampers	Both closing and opening requires manual action (crew member)	Difficult to manoeuvre Sometimes there is a card that tells where the fire dampers are. They may sometimes be difficult to locate (the actual handle)		
4	Master	Managing ventilation	Stopped from the bridge	The placing and marking of ventilators may not be up to standard.		
4	Master	Inform the company emproc				
4	Master	Consider cargo composition	Loading plan (IMDG code)			
4		Manual boundary cooling	If you have a lot of trucks you don't send in a fire team, you can put in water from the sides			
4		(Fixed boundary cooling)				
5		Send a designated person (chief engineer or 2nd engineer) to activate the drencher system (drencher station)	The distance between the engine room and the drencher station varies.			
5	chief engineer / 2nd engineer	Start the pump				
5	chief engineer / 2nd engineer	Activate drencher system				
5	chief engineer / 2nd engineer	Report back to bridge that the valves are open	Radio (Stena also uses a fixed phone)	This communication is important, has led to incidents because of miscommunication		

5	Runner, any crew member	Confirmation of water on deck				
5	chief engineer / 2nd engineer	Decide on extent of activation (sections)	Not required, but in some cases there are markings to tell you which section	Almost always the enumeration in the fire alarm system and actual sections does not match A runner will give important information to tell if the right section has been activated There may be reluctance to activate the drencher if the situation is not fully understood. Will result in electrical faults, clogging etc. (maintenance). Sometimes you don't know exactly what to activate because your sight is blocked. Early activation of the drencher has been identified as one of the most important aspects. Mistakes between valves could be caused by noise, stress Drencher station activities should be explored more deeply, and a different flag (like TT Line or Unity Line)		
5	Master	What is the next step, if the extinguishing system				

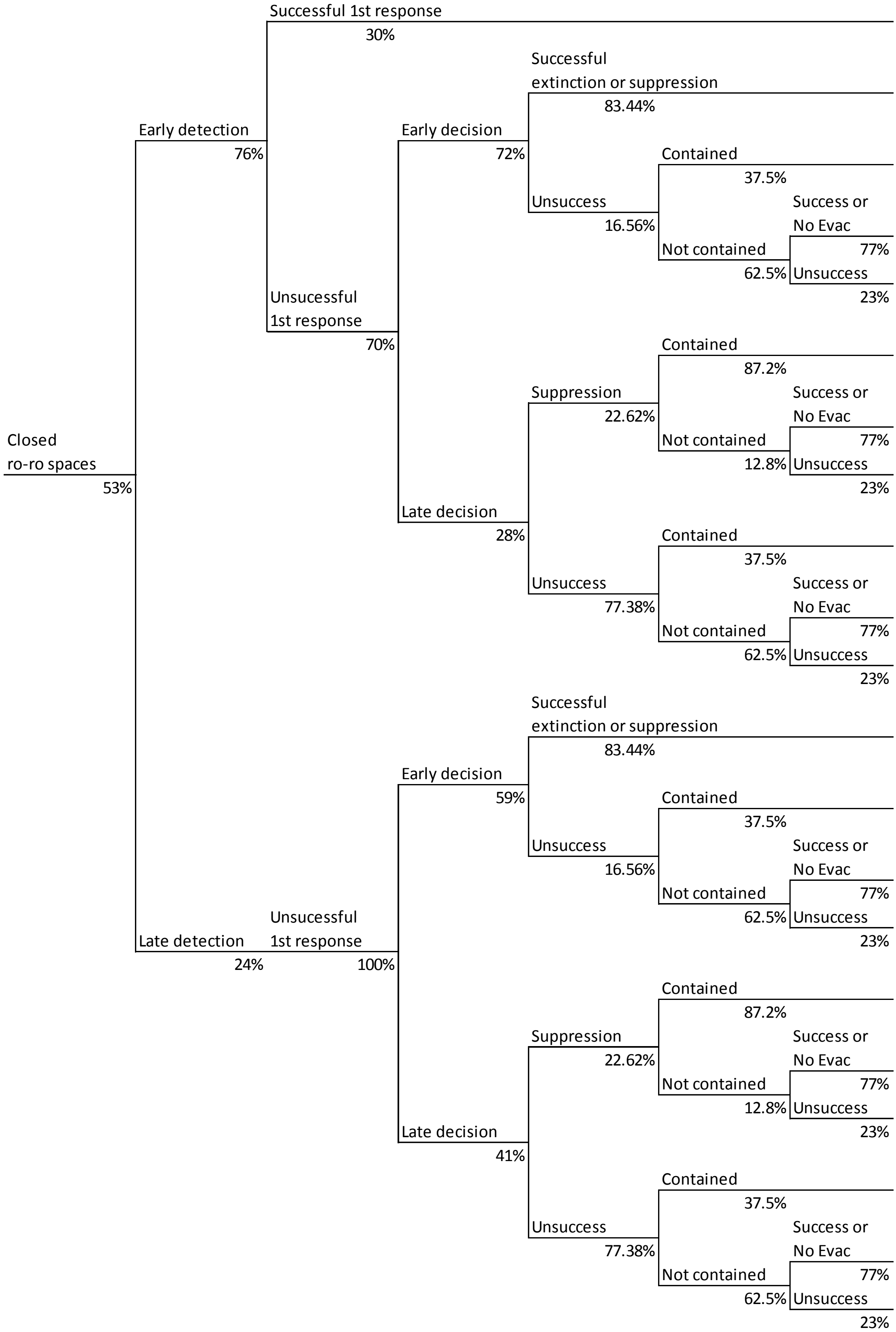
		is not enough? (evacuation)				
5	Master	Assess the situation with power, is there a risk of black-out?				
		Fire squad assembly	When the fire alarm goes, the fire squad assembles at the designated fire station The chief officer/engineer will call the squad members manually if the squad should be activated without a general alarm			
6	Fire squad	Choice of equipment	Information from the bridge (e.g. about dangerous goods)	In many cases, fire squads are not fully familiar with the ship they are on (charter)		
6	Chief engineer / officer, fire squad	Choice of tactics	Briefing about how to approach the fire (routes, team evacuation) Coordination between bridge / different fire stations			
6	Chief engineer / officer	General orders (e.g. on approach, coordination between teams)				
7	Squad leader	GO ask a squad leader				
8	Master	Decision to abort				

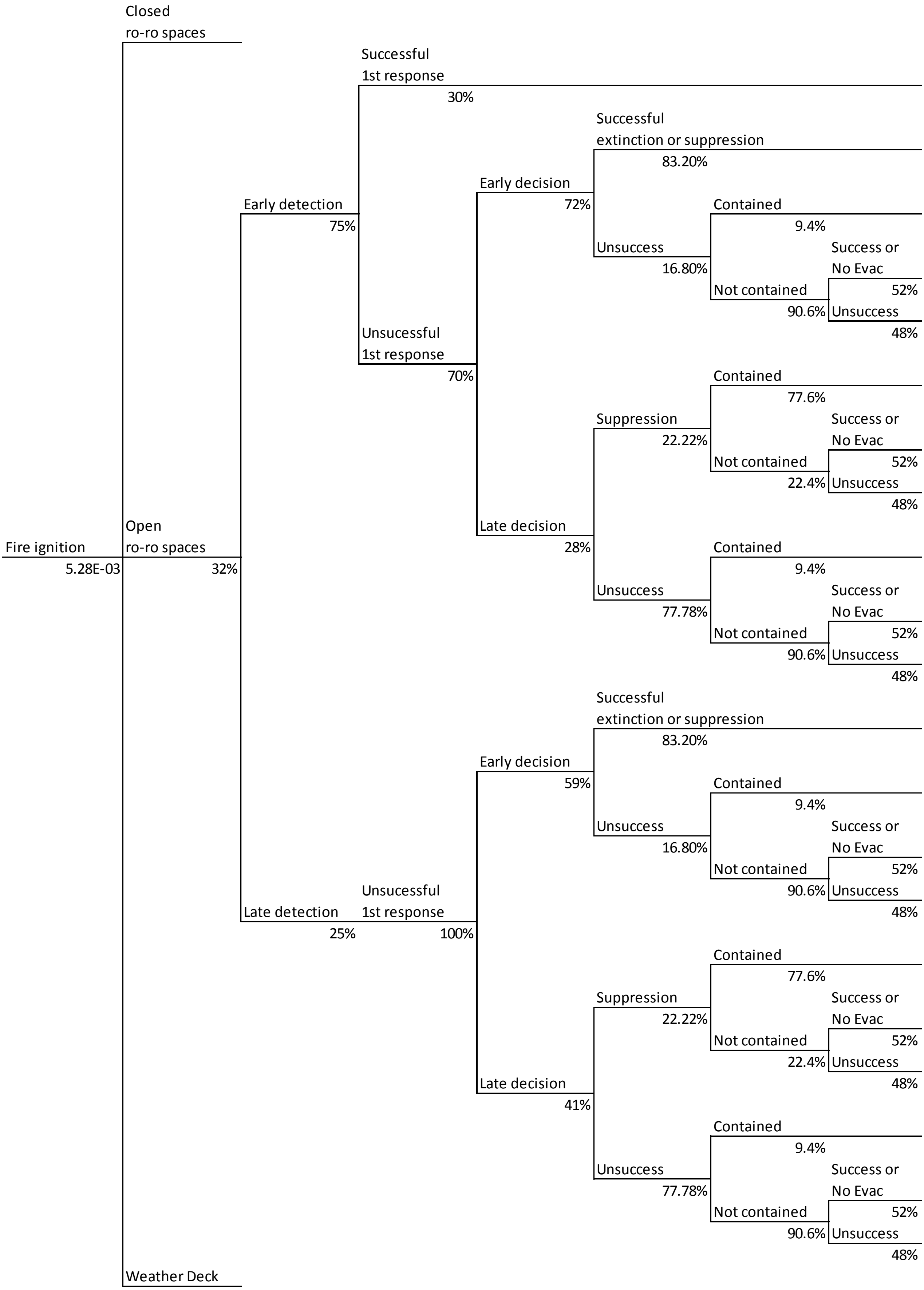
A1.3 Updated Main fire risk model (*Cargo RoPax* – Newbuildings)

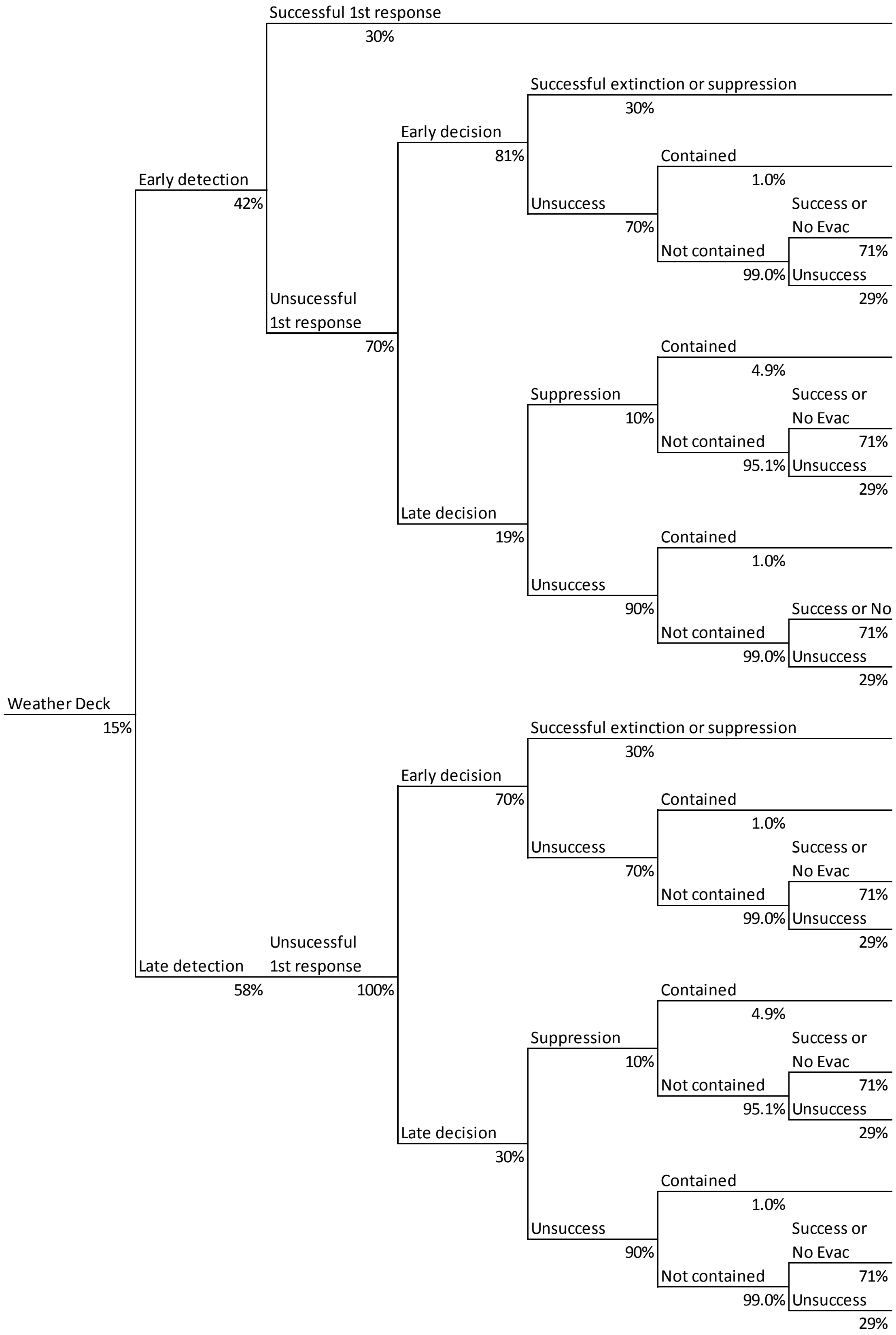



Weather Deck
33%
Early detection
32%
Successful
1st response
30%
Unsucessful
1st response
70%
Early decision
81%
Successful
extinction or suppression
30%
Unsuccess
70%
Contained
5.3%
Not contained
94.7%
Success or
No Evac
67%
Unsuccess
33%
Late decision
19%
Suppression
10%
Contained
11.7%
Not contained
88.3%
Success or
No Evac
67%
Unsuccess
33%
Unsuccess
90%
Contained
5.3%
Not contained
94.7%
Success or
No Evac
67%
Unsuccess
33%
Late detection
68%
Unsucessful
1st response
100%
Early decision
70%
Successful
extinction or suppression
30%
Unsuccess
70%
Contained
5.3%
Not contained
94.7%
Success or
No Evac
67%
Unsuccess
33%
Late decision
30%
Suppression
10%
Contained
11.7%
Not contained
88.3%
Success or
No Evac
67%
Unsuccess
33%
Unsuccess
90%
Contained
5.3%
Not contained
94.7%
Success or
No Evac
67%
Unsuccess
33%

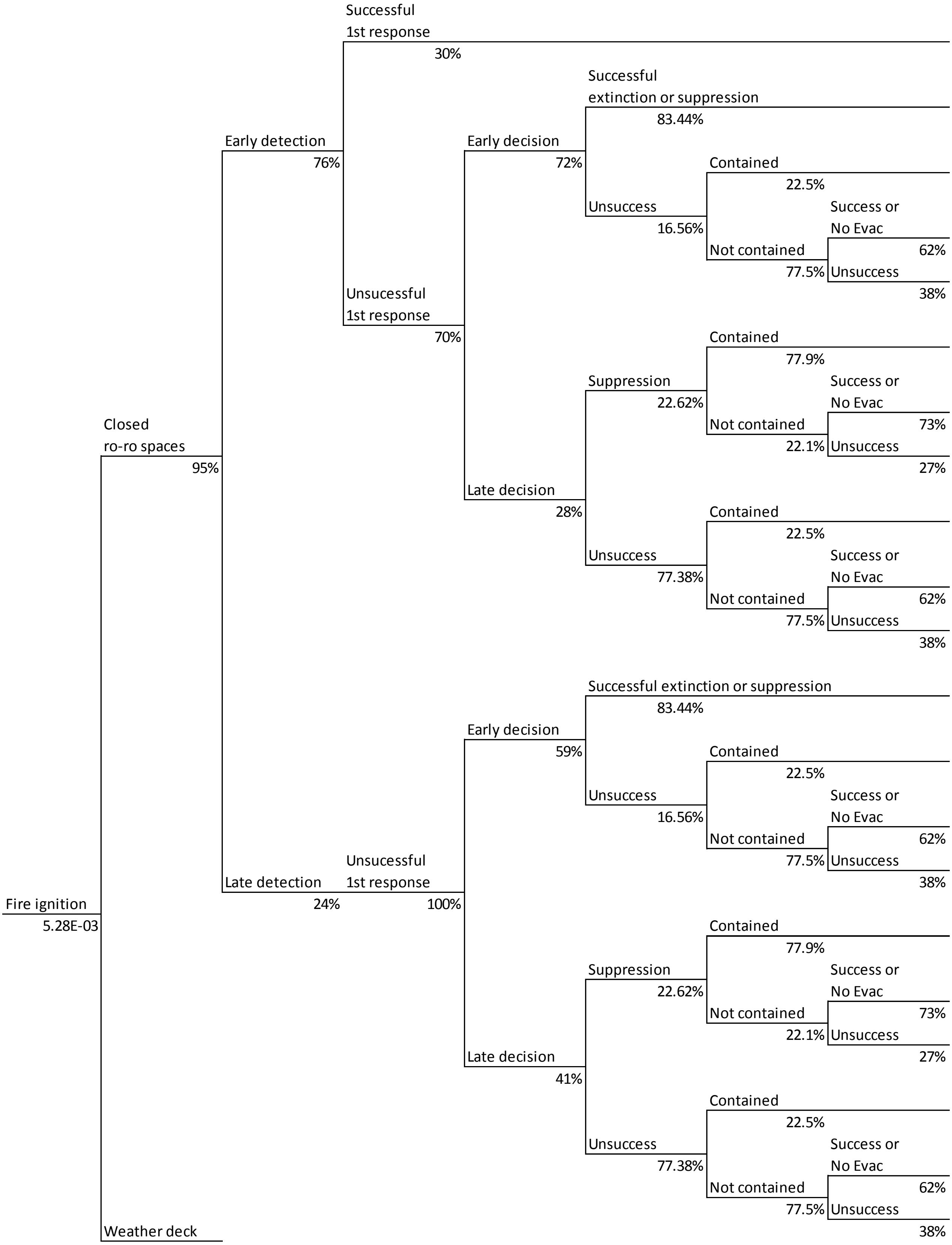
A1.4 Updated Main fire risk model (*Standard RoPax* – Newbuildings)

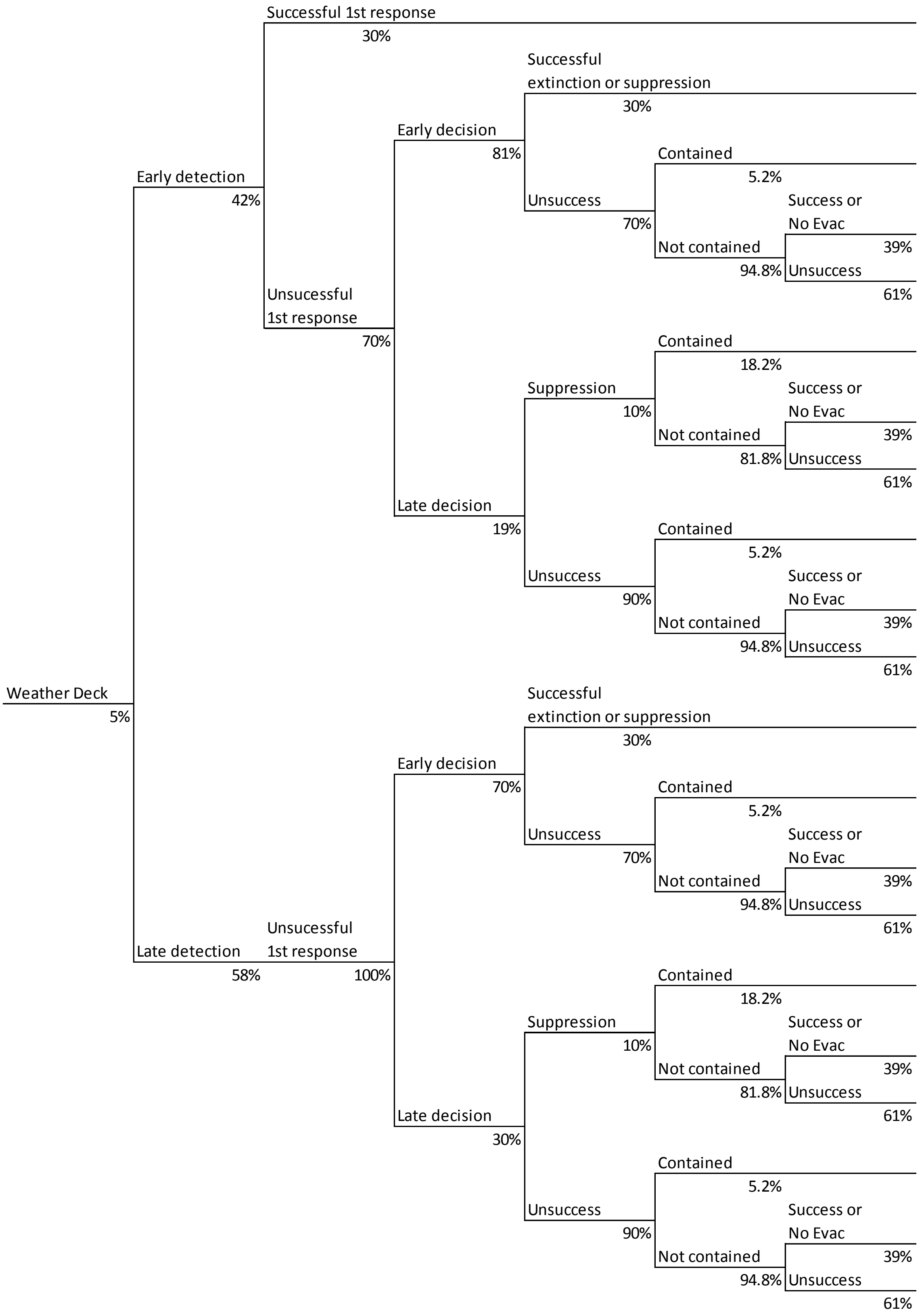



Closed
ro-ro spaces
Successful
1st response
30%
Successful
extinction or suppression
83.20%
Early decision
72%
Early detection
75%
Contained
9.4%
Unsuccess
16.80%
Success or
No Evac
Not contained
52%
90.6%
Unsuccess
48%
Unsucessful
1st response
70%
Contained
77.6%
Suppression
22.22%
Success or
No Evac
Not contained
52%
22.4%
Unsuccess
48%
Open
ro-ro spaces
Fire ignition
5.28E-03
32%
Late decision
28%
Contained
9.4%
Unsuccess
77.78%
Success or
No Evac
Not contained
52%
90.6%
Unsuccess
48%
Successful
extinction or suppression
83.20%
Early decision
59%
Contained
9.4%
Unsuccess
16.80%
Success or
No Evac
Not contained
52%
90.6%
Unsuccess
48%
Unsucessful
1st response
Late detection
25%
100%
Contained
77.6%
Suppression
22.22%
Success or
No Evac
Not contained
52%
22.4%
Unsuccess
48%
Late decision
41%
Contained
9.4%
Unsuccess
77.78%
Success or
No Evac
Not contained
52%
90.6%
Unsuccess
48%
Weather Deck


Weather Deck
15%
Early detection
42%
Successful 1st response
30%
Unsucessful
1st response
70%
Early decision
81%
Successful extinction or suppression
30%
Unsuccess
70%
Contained
1.0%
Not contained
99.0%
Success or
No Evac
71%
Unsuccess
29%
Late decision
19%
Suppression
10%
Contained
4.9%
Not contained
95.1%
Success or
No Evac
71%
Unsuccess
29%
Unsuccess
90%
Contained
1.0%
Not contained
99.0%
Success or No
71%
Unsuccess
29%
Late detection
58%
Unsuccessful
1st response
100%
Early decision
70%
Successful extinction or suppression
30%
Unsuccess
70%
Contained
1.0%
Not contained
99.0%
Success or
No Evac
71%
Unsuccess
29%
Late decision
30%
Suppression
10%
Contained
4.9%
Not contained
95.1%
Success or
No Evac
71%
Unsuccess
29%
Unsuccess
90%
Contained
1.0%
Not contained
99.0%
Success or
No Evac
71%
Unsuccess
29%

A1.5 Updated Main fire risk model (*Ferry RoPax* – Newbuildings)




Weather Deck
5%
Early detection
42%
Successful 1st response
30%
Unsuccessful
1st response
70%
Early decision
81%
Successful
extinction or suppression
30%
Unsuccess
70%
Contained
5.2%
Not contained
94.8%
Success or
No Evac
39%
Unsuccess
61%
Late decision
19%
Suppression
10%
Contained
18.2%
Not contained
81.8%
Success or
No Evac
39%
Unsuccess
61%
Unsuccess
90%
Contained
5.2%
Not contained
94.8%
Success or
No Evac
39%
Unsuccess
61%
Late detection
58%
Unsuccessful
1st response
100%
Early decision
70%
Successful
extinction or suppression
30%
Unsuccess
70%
Contained
5.2%
Not contained
94.8%
Success or
No Evac
39%
Unsuccess
61%
Late decision
30%
Suppression
10%
Contained
18.2%
Not contained
81.8%
Success or
No Evac
39%
Unsuccess
61%
Unsuccess
90%
Contained
5.2%
Not contained
94.8%
Success or
No Evac
39%
Unsuccess
61%

A1.6 Quantification of the Detection fault trees

The quantification is identical for both Existing ships and Newbuildings.

	Cargo RoPax		Standard RoPax			Ferry RoPax	
	Closed	Weather	Closed	Open	Weather	Closed	Weather
System detection failure - Internal failure - **Manual deactivation - Individual det.**	1.0%		1.0%	1.0%		1.0%	
System detection failure - Internal failure - **Manual deactivation - System**	24.2%		24.2%	24.2%		24.2%	
System detection failure - Internal failure - **Technical failure - Individual det.**	0.1%		0.1%	0.1%		0.1%	
System detection failure - Internal failure - **Technical failure - System**	0.3%		0.3%	0.3%		0.3%	
System detection failure - Internal failure - **Contamin. / damage - Individual det.**	0.7%		0.7%	1.1%		0.7%	
System detection failure - Internal failure - **Contamin. / damage - System**	0.3%		0.3%	0.6%		0.3%	
System detection failure - External cause - Poor detector pos. - **Poor location**	0.3%		0.3%	0.3%		0.3%	
System detection failure - External cause - Poor detector pos. - **Poor spacing**	0.1%		0.1%	0.1%		0.1%	
System detection failure - External cause - Type of fire - **Small amount of soot**	0.1%		0.1%	0.1%		0.1%	
System detection failure - External cause - Type of fire - **Too rapid fire**	4.0%		4.0%	4.0%		4.0%	
System detection failure - External cause - Fire position - **Inside cargo / vehicle**	15.0%		15.0%	15.0%		15.0%	
System detection failure - External cause - Fire position - **Close to vent**	1.0%		1.0%	3.0%		1.0%	
System detection failure - External cause - **High airflow**	0.4%		0.4%	0.4%		0.4%	
Late/no manual detection-Fire patrol failure-Not present - **Low frequency**	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
Late/no manual detection - Fire patrol failure - Not present - **Requi. but not present**	3.8%	3.8%	3.8%	3.8%	3.8%	3.8%	3.8%
Late/no manual detection - Fire patrol failure - Quality failure - **Access. problems**	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Late/no manual detection - Fire patrol failure - Quality failure - **Lack of train. / exper.**	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Late/no manual detection - Fire patrol failure - Quality failure - **Lack of equipment**	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Late/no manual detection - Fire patrol failure - Quality failure - **Low motivation**	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%

Late/no manual detection - Crew / pass. det. Failure - **Not present in space**	81.5%	81.5%	64.9%	64.9%	64.9%	65.1%	65.1%
Late/no manual detection - Crew / pass. det. Failure - **Present in space but too far**	5.2%	5.2%	4.1%	4.1%	4.1%	4.2%	4.2%
Late/no manual detection - Crew / pass. det. Failure - Present - **Unwilling of reporting**	0.5%	0.5%	1.2%	1.2%	1.2%	1.2%	1.2%
Late/no manual detection - Crew / pass. det. Failure - Present - **Communic. Failure**	2.0%	2.0%	4.7%	4.7%	4.7%	4.6%	4.6%
Late/no manual detection - **Bridge det. failure**	100.0%	98.0%	100.0%	99.9%	99.0%	100.0%	99.5%

A1.7 Quantification of the Decision fault trees

	Newbuildings Cargo RoPax & Standard RoPax & Ferry RoPax				Existing ships Cargo RoPax & Standard RoPax & Ferry RoPax			
	Early		Late		Early		Late	
	Closed / Open	Weather	Closed / Open	Weather	Closed / Open	Weather	Closed / Open	Weather
Late alarm interpretation - **Alarm is wrongly dismissed**	3.0%		0.1%		3.0%		0.1%	
Late alarm interpretation - Delayed acknowledgment - Delayed alarm handling - **Alarm is missed**	0.5%		0.5%		0.5%		0.5%	
Late alarm interpretation - Delayed acknowledgment - Delayed alarm handling - **Time lost on inf. Integration**	2.0%		4.0%		3.0%		6.0%	
Late alarm interpretation - Delayed acknowledgment - Delayed alarm handling - **Inf. Misinterpreted**	1.0%		2.0%		1.0%		2.0%	
Late alarm interpretation - Delayed acknowledgment - **Travel time on bridge**	0.1%		0.2%		0.1%		0.2%	
Late confirmation - **Late tech. Conf.**	90.0%		90.0%		90.0%		90.0%	
Late confirmation - Late manual confirmation - Late arrival at detector point - **Late deployment of runner**	1.0%		2.0%		1.0%		2.0%	
Late confirmation - Late manual confirmation - Late arrival at detector point - **Long travel time to detection point**	3.1%		6.2%		3.1%		6.2%	
Late confirmation - Late manual confirmation - Late localisation - **Difficult environment**	3.0%	1.0%	6.0%	2.0%	3.0%	1.0%	6.0%	2.0%
Late confirmation - Late manual confirmation - Late localisation - **Inadequate strategy**	2.0%	2.0%	0.0%	0.0%	2.0%	2.0%	0.0%	0.0%
Late confirmation - Late manual confirmation - Late localisation - **Inadequate equipment**	2.0%	2.0%	0.0%	0.0%	2.0%	2.0%	0.0%	0.0%
Late confirmation - Late manual confirmation - **Failure of communication**	5.0%	5.0%	10.0%	10.0%	5.0%	5.0%	10.0%	10.0%
Late assessment - **Poor availability of key personnel**	5.0%	5.0%	10.0%	10.0%	5.0%	5.0%	10.0%	10.0%
Late assessment - **Insufficient cargo inf**	1.0%	1.0%	2.0%	2.0%	1.0%	1.0%	2.0%	2.0%
Late assessment - **Insufficient competence**	5.0%	5.0%	10.0%	10.0%	5.0%	5.0%	10.0%	10.0%

A1.8 Risk control measures – Detection

List of identified risk control measures (RCMs). RCMs considered as “low hanging fruit” are presented separately in A1.9.

RCM	Potential effect (for detection)	Category
Combined smoke and heat detection	Active systems when smoke detection is deactivated Follow fire development/spread and lower risk of wrong decision	Engineering
Fibre optic linear heat detection (complementing smoke detection)	Robust system, low false alarm rate Active systems when smoke detection is deactivated Follow fire development/spread	Engineering
Smoke detection in ventilation outlets/ducts	Detection of smoke when smoke is ventilated away.	Engineering
Thermal imaging cameras with fire detection algorithms (primarily on weather decks)	Detection of fire when smoke and heat is ventilated away Detection of thermal event before fire starts Localization of fire	Engineering
Conventional flame detection (primarily on weather decks)	Detection of fire when smoke and heat is ventilated away.	Engineering
CCTV covering all decks	Localization of fire Smoke/flame automatic detection potential (for the future)	Engineering
Gas detection	Pre-warning of potential fire/explosion	Engineering
Detector drone or camera on rail in deckhead or on floor	Increased detection ability in case of much cargo	Engineering
Lower alarm threshold values	Faster detection	Engineering
Smoke movement algorithms integrated in conventional smoke detection system	Better localization of fire at smoke alarm	Engineering
Extra redundancy (e.g. double loop detector wiring)	Lower risk of system failure Continuous monitoring after initial fire	Engineering
More frequent (better) maintenance of detection system (at least yearly service from manufacturer)	Fewer faulty alarms and false alarms Lower risk of detection system failure and delayed detection	Procedural
Better addressability (incl. logical addresses and correlation between detection and drencher sections)	Faster response and lower risk of wrong decisions Localization of fire and lower risk of activation of wrong drencher section	Engineering/Inherent
Better design/interface of detection system (more function based and intuitive, e.g. maps instead of alarm list and automatic display of relevant cameras)	Faster response and lower risk of wrong decisions No risk that a second alarm remains unnoticed	Engineering/Inherent
Permanent closure of openings	Prevent smoke and heat to be ventilated away	Inherent
Reduction of openings (e.g. net)	Prevent smoke and heat to be ventilated away due to strong winds	Engineering

Increased frequency of fire patrols	Faster response, localization Fire detection on weather decks	Procedural
Spacing of cargo for fire patrol access	Increased detection ability in case of much cargo	Inherent/Procedural
Dog patrols	Increased detection ability in case of much cargo	Engineering
Additional detection means in AFV areas (means that specific AFV areas must be identified)	Faster detection of potential AFV fire	Engineering
Loading configuration of AFVs (mapping of AFVs on decks)	Faster detection of potential AFV fire Limit consequences of potential AFV fire	Procedural
Improved standardized detection tests and/or simulations	Suitable detection technology and sensor position to be able to detect fires in windy conditions. Lower risk of detection failure due to improper installation/design	Engineering/Procedural
Presence of fire safety engineer during installation/design	Lower risk of detection failure due to improper installation/design (location, spacing, openings, ventilation)	Procedural
More frequent (better) maintenance of detection system (at least yearly service from manufacturer)	Fewer faulty alarms and false alarms Lower risk of detection system failure and delayed detection	Procedural
Better addressability (incl. logical addresses and correlation between detection and drencher sections)	Faster response and lower risk of wrong decisions Localization of fire and lower risk of activation of wrong drencher section	Engineering/Inherent
Better design/interface of detection system (more function based and intuitive, e.g. maps instead of alarm list and automatic display of relevant cameras)	Faster response and lower risk of wrong decisions No risk that a second alarm remains unnoticed	Engineering/Inherent
Continuous monitoring of vehicle decks when passengers have access	Lower risk of false alarms due to starting engines Faster response	Procedural
Automatic activation of detection system (e.g. when main engine is started)	Lower risk of deactivated system in combination with no presence of crew	Engineering
Competence of crew with regard to smoke movement	Better localization of fire at smoke alarm	Procedural
Smartphone application for fire detection/localization	Faster response Localization of fire	Engineering
Mobil phones connected to the ship phone system	Ensure good communication, faster response	Engineering/Inherent
More fixed relay stations	Ensure good communication, faster response	Engineering/Inherent
Key personnel shall carry radio at all times	Ensure good communication, faster response	Engineering/Procedural
More fixed communication points (MOCPs or phones)	Ensure good communication, faster response	Engineering/Inherent
Keeping ABs and fire patrols the same nationality/language.	Ensure good communication, faster response	Procedural
Fire alarms immediately sound throughout crew accommodation (No built-in delay with alarm only on bridge/ECR)	Faster response	Procedural

A1.9 Low hanging fruits

List of low hanging fruits (LHFs), i.e. RCMs with low estimated cost and which can be recommended without further evaluation. Note that some of the LHFs eventually can be costly for specific implementations, depending on current procedures and ship design.

LHF	Short description
Clear signs and section markings for detection/drencher zones	As smoke rapidly build-up in the ro-ro space, it may be difficult to visually identify in which drencher section the source of ignition is situated (see URD accident). Markings in the ro-ro spaces showing the sections (at eye height) can support the crew in this identification, therefore ensuring a better communication and faster and more accurate response.
Bulletins of learned lessons	Experience-sharing (positive and negative) may highlight some critical aspects of detection related tasks (e.g. identification of high risk areas, common sources of ignition) and participate to the improvement of the safety culture.
Ensure ship familiarization	Every new crew member follows an induction program which includes ship familiarization, but the familiarization procedure varies in the fleets and is sometimes not followed up.
Frequent training, familiarization, debriefing	Fire drills (and subsequent debriefing) should include the detection part.
Improved instructions to crew and passengers	Instructions, improved information, signs clarifying to press the MOCP as soon as there is a small fire, symbols. Well-designed instructions and guides to passengers.
Sufficient equipment to fire patrols, first responders, etc.	Correct outfit and equipment (e.g. IR camera, gas sniffers, first response set) contribute to personnel confidence to perform correct actions in case of fire, increased fire safety awareness and possibly earlier detection.
Training and motivation of fire patrols, first responders, ABs, etc.	Requirements for fire patrols may be implemented as it is important that crew members responsible for the fire patrols are fit for purpose. Counteract low motivation, whether it is due to physical or social attributes.
No un-authorized charging of vehicles	Charging of electric vehicles may constitute an increased fire hazard. Fire patrols should remove charging connections if found.
Good reefer unit policy	Ship operators cannot control the condition of vehicles and reefer units that are brought on to the ship, but increased awareness and vigilance, as well as dedicated reefer unit policy (e.g. dedicated areas, dubious quality rejected, power transfer cable condition and policy) allow for a lower risk of fire and faster response in case of fire.
Supply enough cables/connections to avoid use of diesel generators	Reefer units should not be allowed to operate on their own diesel generator power supply and should be connected to the ship's grid in order to reduce the risk of fires and number of false alarms. To this end, sufficient number of cables should be carried on board.
The possibility to deactivate only smoke sensors (e.g. heat or flame detection active)	Lower risk of deactivated system in combination with no presence of crew.
The possibility to deactivate section/deck/ individual detectors instead of the complete detection system	Lower risk of deactivated system in combination with no presence of crew.
Restricted passenger access to ro-ro spaces	Lower risk of false alarms due to starting engines. This provision is already included in SOLAS.

Improved safety culture	Safety culture encourages local adaptation and decision-making.
Maintenance plan for cleaning smoke detectors	Maintenance plan for cleaning smoke detectors should be developed to lower risk of delayed detection and reduce the number of faulty alarms and false alarms.
Keep first responders/runners in duties close to high risk areas	Keep first responders/runners in duties close to high risk areas would ensure faster confirmation and/or first response, increasing the probability of success of extinction with fire extinguishers.
Improved accessibility for fire patrols	Improved accessibility allows for better identification of the type of fire (electrical, battery, DG, pool fire, new energy carriers), and allows fire patrols to check any cargo units.
Designated radio for ABs	ABs (and others involved in fire patrols) shall have a designated radio at all times to ensure good communication and faster response.
Improved call point positions and instructions	Call points should be situated in closed proximity of a fire extinguisher, with clear instructions and intuitive design, which cannot be mistaken for being something else (e.g. door opener).

A1.10 Ranking matrix (Detection)

		Cost efficiency				
		Very Low	**Low**	**Medium**	**High**	**Very High**
Risk Red	**Very High**					
	High		* Combined smoke and heat detection * Fibre optic linear heat detection * Permanent closure of openings * Conventional flame detection * Thermal imaging cameras with fire detection algorithms * Additional detection means in AFV areas * CCTV cameras on all decks * Increased number of fire patrols * Detector drone or detector/camera on rail in deckhead or on floor			
	Medium	* Better design/interface of detection system * Separation of cargo for fire patrol access * Closure of openings upon detection * Loading configuration of AFVs * Gas detection * Smartphone application for fire detection/localization	* Possibility to de-activate a section/deck/individual detectors instead of the complete detection system * Improved standardized detection tests and/or simulations * More fixed relay stations * Ensure accessibility everywhere for fire patrols * Keeping the ABs or at least those on fire patrol the same nationality/language * Better/more frequent maintenance of detection system * Fire alarms immediately sound throughout crew accommodation * Continuous monitoring of vehicle decks when passengers have access * More fixed communication/phones			
	Low	* Mobil phones connected to the ship phone system * Extra redundancy * Dog patrols * Restricted use of diesel generators * Better cargo securing * Lower alarm threshold values * Smoke movement algorithms integrated in conventional smoke detection system	* Reduction of openings * More fixed communication/phones * Smoke detection in ventilation outlets/ducts * Competence of crew with regard to smoke movement * Automatic activation of detection system * Presence of fire safety engineer during installation/design			
	Very Low					

A1.11 Ranking matrix (Decision)

Newbuildings		Cost efficiency				
		Very Low	Low	Medium	High	Very High
Risk Red	Very High		RCO_03: Improved technical aids for fire identification and monitoring	RCO_06: Preconditions for Early Activation of Drencher System RCO_01: Alarm System Design & Integration RCO_02: Improved markings/signage for wayfinding and localisation		
	High		RCO_05: Separation of cargo for accessibility RCO_04: CCTV system designed for fire identification / monitoring			
	Medium					
	Low					
	Very Low					

Existing ships		Cost efficiency				
		Very Low	Low	Medium	High	Very High
Risk Red	Very High		RCO_01: Alarm System Design & Integration RCO_03: Improved technical aids for fire identification and monitoring RCO_05: Separation of cargo for accessibility	RCO_06: Preconditions for Early Activation of Drencher System RCO_02: Improved markings/signage for wayfinding and localisation		
	High		RCO_04: CCTV system designed for fire identification / monitoring			
	Medium					
	Low					
	Very Low					

A1.12 Human Factors Assessment of Fire Alarm Systems & Tools

1. When a fire alarm occurs, what indications do you receive?
    a. What about in the case of additional alarms during an ongoing fire?
2. How easy is it do perceive fire alarms on the bridge?
    a. Is there noise or activities on the bridge that may reduce the perception of alarms? *E.g. noise from machinery, other systems, communication*
    b. Could alarm signals or other signals disrupt work during an ongoing fire? How?
    c. Is it possible to silence alarm signals without risk of losing or forgetting information? How?
3. When a fire alarm is received, which systems and other tools on the bridge are used to determine the location of the fire?
    a. How do you determine the location of the fire?
    b. Is it easy to obtain the information needed?
4. After the fire is located, do you use other systems or tools on the bridge to make decisions about first response? Which ones?
5. Are the systems and tools that you employ in the case of fire
    a. Accessible? Logically grouped. Available quickly without unnecessary movement. Work for all relevant users irrespective of age, vision and hearing.
    b. Easy to use? Easy to comprehend, intuitive, simple and fast in operation.
6. Do they function in the same way as other alarm and information systems on the bridge?
    a. Vocabulary, graphics and layout, how information is presented, how the system is operated, etc.

A1.13 Participants of the fire detection hazard identification workshop and their expertise

HazId participants	**Organization**	**Profession / Competence**	**Role / responsibility**
Franz Evegren	RISE	Research Scientist in Fire Safety Engineering	Facilitator
Michael Rahm	RISE	Director of the Fire Dynamics Department	
Pierrick Mindykowski	RISE	Research Scientist in Fire Safety Engineering	Scribe
Ola Willstrand	RISE	Expert in Fire Detection	
Ying Zhen Li	RISE	Research Scientist in Fire Safety Engineering	
Staffan Bram	RISE	Expert in Human Factors and Design	
Helene Degerman	RISE	Project leader and PhD student in organisational safety	
Jérome Leroux	BV	Risk Analysis Engineer	WP Leader
Antoine Cassez	BV	Fire Safety Engineering	
Blandine Vicard	BV	Rule Development Engineer	
Stephane Quievreux	BV	Technical Adviser for Fire & Safety	
Fredrik Efraimsson	Stena Teknik	M.Sc. Naval Architect	
Peter Harrysson	Stena Line	Captain on RoPax	
Hans Corneliusson	Stena Line	Fleet Manager, former chief engineer	
Markus Parmdal	Stena Line	AB on RoPax, onboard fire fighter	
Sifis Papageorgiou	EMSA	Project Officer, Ship Safety & Marine Equipment	Observer / Project officer

A1.14 Participants of the fire decision hazard identification workshop and their expertise

HazId participants	**Organization**	**Profession / Competence**	**Role / responsibility**
Franz Evegren	RISE	Research Scientist in Fire Safety Engineering	
Michael Rahm	RISE	Director of the Fire Dynamics Department	
Pierrick Mindykowski	RISE	Research Scientist in Fire Safety Engineering	
Ola Willstrand	RISE	Expert in Fire Detection	
Ying Zhen Li	RISE	Research Scientist in Fire Safety Engineering	
Staffan Bram	RISE	Expert in Human Factors and Design	Moderator
Helene Degerman	RISE	Project leader and PhD student in organisational safety	
Jérome Leroux	BV	Risk Analysis Engineer	WP Leader
Antoine Cassez	BV	Fire Safety Engineering	
Blandine Vicard	BV	Rule Development Engineer	
Stephane Quievreux	BV	Technical Adviser for Fire & Safety	
Fredrik Efraimsson	Stena Teknik	M.Sc. Naval Architect	
Peter Harrysson	Stena Line	Captain on RoPax	
Hans Corneliusson	Stena Line	Fleet Manager, former chief engineer	
Markus Parmdal	Stena Line	AB on RoPax, onboard fire fighter	
Sifis Papageorgiou	EMSA	Project Officer, Ship Safety & Marine Equipment	Observer / Project officer

A2 SENSITIVITY AND UNCERTAINTY ANALYSES

This annex is divided into two parts. The first part deals with the methodology used for the nodes in the event tree that were investigated through fault tree analysis, whereas the second part deals with the methodology used for the remaining nodes.

Fault tree uncertainty analysis

The procedure outlined below was performed on all nodes in the event tree that were investigated through fault tree analysis (FTA):

- Detection (Tier 2)
- Decision (Tier 4)
- Extinguishment (Tier 5)[23]
- Containment (Tier 6)

Due to the inherent properties of fault trees, the values assigned to bottom nodes are cascaded to the top event, and thus reflected in the event tree given that the top event in a fault tree corresponds to one or more branches under a specific node in the event tree. Consequently, it was necessary to define probability distributions for bottom nodes in the fault trees in order to account for uncertainties associated with a top event.

The bottom nodes that were considered uncertain were assigned beta distributions $beta_{distr}(\alpha, \beta, P_{bottomNode})$ where $P_{bottomNode}$ was the static value of the bottom node probability and the parameters α and β were determined through the following process:

1. Each bottom node considered uncertain was assigned a confidence level based on the perceived uncertainty of $P_{bottomNode}$. The confidence levels, low, medium, and high, each corresponded to a number N:
    a. $N_{lowConfidence} = 10$
    b. $N_{mediumConfidence} = 50$
    c. $N_{highConfidence} = 250$
2. Once the confidence level was determined, α and β could be calculated for the relevant bottom node:

$$\alpha = (N + 1)P_{bottomNode}$$

$$\beta = (N + 1)(1 - P_{bottomNode})$$

Uncertainty analysis for remaining nodes

For the node *Ignition*, a log-normal distribution was used. The frequency of fires in ro-ro spaces was estimated based on historical data (section 8.1.2). Based on the assumption that accidents are Poisson distributed, the same methodology as the one used in the EMSA III study (EMSA, 2015) was followed for the determination of the log-normal parameters.

For the node *Deck type*, a triangular distribution was used. The lower limit, mode, and upper limit were ship dependent. The general line of reasoning was however to use distributions that would not lead to unreasonable values with regard to the proportionality of deck types. For example, the distributions for the Standard RoPax were defined such that the percentage of closed ro-ro space would not exceed the percentage for open ro-ro space.

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[23] No FTA was performed for Extinguishment/Weather deck, hence the need for an alternative approach. A simple symmetric triangular distribution (lower limit=0,50, mode=0,70, upper limit=0,90) was used to account for the uncertainty associated with these outcomes.

For the node *First response*, a triangular distribution with the $lower\ limit = 0{,}50$, $mode = 0{,}70$, and upper $limit = 0{,}90$ was used.

For the node *Evacuation*, a simple model was developed and a triangular distribution with the $lower\ limit = 0{,}0$, $mode = 0{,}25$, and $upper\ limit = 0{,}50$ was used for the model parameter *unfavorable wind*.

A3 LIST OF ABBREVIATIONS

AB:	Able seaman
ACPH:	Air changes per hour
AFV:	Alternatively Fuelled Vehicles
ATSFR:	Available Time for Safe First Response
BA:	Breathing Apparatus
CEA:	Cost-Effectiveness Assessment
CCTV:	Closed-Circuit Television
CFD:	Computational Fluid Dynamics
CI:	Confidence Interval
CLIA:	Cruise Lines International Association
CNG:	Compressed Natural Gas
COP:	Common Operational Picture
EMSA:	European Maritime Safety Agency
EN:	European Norm
E/R:	Engine Room
EU:	European Union
FC:	Fuel Cell
FDS:	Fire Dynamics Simulator
FED:	Fractional Effective Dose
FMEA:	Failure Mode and Effects Analysis
FSA:	Formal Safety Assessment
FSS:	International Code for Fire Safety Systems
GA:	General Arrangement
GCAF:	Gross Cost of Averting a Fatality
GDP:	Gross Domestic Product
GT:	Gross Tonnage
HazId:	Hazard Identification
HRR:	Heat Release Rate
IACS:	International Association of Classification Societies
IEC:	International Electrotechnical Commission
IMDG:	International Maritime Dangerous Goods Code
IMO:	International Maritime Organization
IR:	Infrared
LHF:	Low-Hanging Fruit
LLL:	Low Location Lighting
LM:	Lane Metre

LNG:	Liquefied Natural Gas
LPG:	Liquefied Petroleum Gas
LQI:	Life Quality Index
MCA:	UK Maritime Coastguard Agency
MEPC:	Marine Environment Protection Committee
MOCP:	Manual Operated Call Point
MSC:	Maritime Safety Committee
MVZ:	Main Vertical Zone
MW:	Megawatt
NCAF:	Net Cost of Averting a Fatality
NDM:	Naturalistic Decision-Making
NPV:	Net Present Value
PLC:	Potential Loss of Cargo
PLL:	Potential Loss of Life
PLS:	Potential Loss of Ship
PS:	Portside
R&D:	Research and Development
RCM:	Risk Control Measure
RCO:	Risk Control Option
RPD:	Recognition-Primed Decision-Making
RTI:	Response Time Index
RTSFR:	Required Time for Safe First Response
SA:	Situation Awareness
SB:	Starboard
SFPE:	Society of Fire Protection Engineers
SOLAS:	Safety of Life at Sea
SRtP:	Safe Return to Port
UI:	Unified Interpretation
UR:	Unified Recommendation
UV:	Ultraviolet
TRL:	Technology Readiness Level
TV:	Threshold Value
VTS:	Vessel traffic service
WD:	Weather Deck
WP:	Work Package
WYFIWYF:	What You Find Is What You Fix
WYLFIWYF:	What You Look For Is What You Find